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Dental Variation In Malaysian Populations With Application To Human Identification

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Mohd Fadhli Bin Khamis
BDS, Grad. Dip. Foren. Odont.

Forensic Odontology Unit
Dental School
The University of Adelaide

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Abstract

The aim of this study was to carry out a detailed analysis of dental crown size and morphology in the four main ethnic groups living in Malaysia; Malays, Chinese, Indians and Negritos. The particular focus was to develop methods that could be applied in forensic cases where the need to determine identity is hampered by lack of detailed dental records. The outcomes of the study also have application in describing population affinities and histories in a broader anthropological context.

Recent mass disasters have highlighted the important role played by the dentition in confirming the identity of deceased persons. Although the use of dental structures to determine age is well accepted, objective methods to discriminate gender and ethnicity based on dental features have not been described or tested to any great extent. There are, however, situations where such methods, if shown to have good predictive value, would make a valuable contribution to forensic investigations.

Dental impressions of 790 individuals were obtained by the author over a 3-month period and dental models were constructed from these impressions. Tooth size and dental crown morphology were recorded from the dental models using digital callipers and visual observation. The data were analysed to determine within- and between-group variation using both univariate and multivariate analyses. Models to predict ethnicity and sex were developed and tested for accuracy.

Metric tooth size data revealed no significant trends in directional asymmetry in any of the groups. The Chinese sample showed dimensional variability in the dentition which conformed to morphogenetic field theory and also displayed the most sexual dimorphism in crown size. In terms of tooth size, the Malays and Chinese were close, while the Negritos were distinctly separated from the other groups.

Morphological crown traits tended to be expressed symmetrically with little evidence of sexual dimorphism. Phenetic distance estimates based on crown morphology indicated that Malays, Chinese and Negritos could be grouped together to represent a Mongoloid group. The Indians formed a separate group who displayed Indo-european features in their dentitions.

Tooth size data were used alone to generate sex prediction models in all four groups, and then they were combined with selected crown traits to evaluate ethnicity prediction models between Malays, Chinese and Indians.

The most successful sex discrimination results, at 88% accuracy, were observed in the Chinese group. Models generated for samples where groups were combined, to simulate a

situation where ethnicity was unknown, still provided over 80% accuracy in determining sex. The ethnicity discrimination rates between Malays, Chinese and Indians were relatively low, although the models that were developed performed better than chance. When Malays and Chinese were pooled to form a Mongoloid group, predictability improved to 72% accuracy. The use of logistic regression analysis on combined metric and non-metric data improved the success rates to 87.6 – 91.5%.

This thesis provides the first comprehensive description of the dental characteristics of the four main ethnic groups in Malaysia. The results have shown that predictive models can be developed from dental data with sufficient predictive power to discriminate between the sexes and ethnic groups. These models are potentially valuable in forensic cases where there are low rates of dental caries or few dental restorations, or where dental records are incomplete. The results are also valuable in a broader anthropological context in improving our understanding of the affinities and histories of the different ethnic groups living in Malaysia.

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to my best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

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Structure of thesis

This thesis has been structured as ten separate chapters, each with its own set of references. The format of each chapter has been organised to facilitate submission of material to journals for publication. This approach has led to a small amount of repetition but it is hoped this will not detract from the reader's enjoyment - in fact, the repetition may help to maintain a continuity of thought. The appendices are presented in a separate volume to keep the length of volume 1 manageable.

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Chapter 1 Introduction

1.1 The importance of the identification process

Human identity has significant social and legal impact for both living and deceased persons. Generally, for living persons, identity is important for security reasons such as banking transactions, access to secure sites and facilities and in preventing falsification of insurance claims, to name but a few. The importance of identification of the deceased has been frequently addressed for single and multiple casualties (Pretty and Sweet, 2001), and in homicide investigations (Brown, 1982; Rudnick, 1984; Rothwell *et al.*, 1989; Whittaker, 1994).

From a legal perspective, death certificates cannot be issued unless the identity of the person in question has been confirmed. A death certificate is an important document in enabling a burial permit to be issued, for a family to claim life insurance and assets, and for a spouse to remarry. An official burial ceremony will be delayed without a death certificate. This has a major impact in Muslim communities since the dead are required to be buried as soon as possible after death. Under Malaysian civil law, without a death certificate widow status and access to a spouse's assets are frozen for seven years (Evidence Act 1950). This also applies to Muslim women, under the enactment of Muslim Family Section 41(1) No. 1/1983, with seven years being required before the declaration of death can be made by the Syariah court. This lengthy period will obviously mean that many dependants will suffer financial hardship, although if any insurance claims and assets can be settled smoothly after the loss of the sole breadwinner, a family may be able to resume their regular life reasonably well.

Confirmation of identity can also be of considerable significance in civil and police investigations following deaths. In aviation disaster investigations, identification of victims can prove crucial in the reconstruction phase. From the nature and extent of injuries of victims and matching against seat allocations, investigators may be able to determine the cause of an accident. These findings can then be used to improve safety and prevent similar accidents in the future.

It is worth reviewing the Albury Pyjama Girl murder case of 1934 (Brown, 1982) to gain some insight into the importance of identification in homicide cases. The murderer, who was the husband of the victim, was only brought to justice ten years after the murder. The long delay was due to an inability to positively identify the victim. The victim's face had been badly burnt, so the police had to rely on comparison of teeth with dental records and a facial reconstruction. Unfortunately, the dentist who performed the original dental examination had mistakenly charted

the upper first molar as an upper second molar and also overlooked several restorations on the premolars. The facial reconstruction added further confusion to the identity of victim. It was ten years later, when another dentist examined the victim and corrected the mistakes, that a positive identification was finally made and the murderer arrested.

Similar issues are important for the Royal Malaysian Police. Identification of a victim is the crucial starting point in an investigation (personal communication), which then leads to a search for the last person seen in contact with the victim, and then to possible motives.

Social importance of correct identification of individuals encompasses alleviating family grief as well as fulfilling the right of the deceased to have a proper burial in accordance with religious, cultural and traditional customs. Confirming that a loved one has passed away can provide relief to a family. The Malaysian population consists of several different ethnic groups with different religions, cultures and traditions. Each of them would wish for and expect a burial in accordance with their beliefs as a last right of honour for the deceased.

The first aviation disaster in Malaysian history occurred in 1977 and claimed 100 lives (Nambiar *et al.*, 1997). Due to the nature of the remains, most of the unidentified bodies were buried in a mass grave. For some families this was a devastating experience when no confirmation of identity was made, combined with the fact that all unidentified bodies from different religions and beliefs were buried together. With the advancement of technology and research in forensic identification sciences, we hope mass burial will never be the outcome for Malaysians in the future. Thus, this project explores possibilities for using the morphology of teeth for human identification in addition to the more common practice of comparing dental treatments, in the hope that the more alternatives that are available, the better the chances of positive identification.

1.2 Methods for identification of human remains

The most common methods used for human identification are visual recognition and personal belongings. Visual identification relies on unique soft tissue and underlying hard tissue features. Facial contour, skin and eye color, and hairstyles are subject to changes with time and especially to post-mortem changes. The potential for mistaken identity is so high that this method should be avoided in forensic cases. When family members are asked to visually identify a body, they are vulnerable to false positive and negative identifications, due to the strong emotions associated with the situation. Personal belongings should only be used as corroborative evidence in the identification process as they are readily interchangeable, whether unintentionally or otherwise.

More reliable scientific methods should preferably be used in forensic investigations. The widely accepted methods are fingerprints, comparison of dental records and deoxyribonucleic acid (DNA) analysis. These three scientific methods share similar principles in attempting to establish individual identity. In order to reach a conclusion, known latent evidence is required for comparison. Latent evidence refers to, for example, fingerprints recorded in Police databases or latent fingerprints found on a glass or kitchen-ware in a house, ante-mortem dental records in a clinic, or human cells found on a tooth brush known to belong to the suspect. Another tenet is that the three features-fingerprints, dental record comparisons and DNA-have been shown to be unique to an unrelated individual. The concept of individuality is based on the low probability of finding unrelated persons with identical features. From recent studies on American populations, both DNA and dental comparison have approximately similar diversity estimates of 0.99 and 0.98 respectively (Adams, 2003). Diversity estimates show the degree of distinctiveness, with values closer to one showing greater distinctiveness (very high individuality) and indicating that the probability for evidence coming from two different persons in that population with similar characteristics is less than two percent.

Not every forensic situation provides both latent and post-mortem information sufficient for comparison. There are occasions where a combination of methods needs to be employed. In addition, each of the three scientific methods discussed above has its own limitations. Fingerprints obtain their characteristics from the epidermal ridges that can be altered in some post-mortem situations, particularly after incineration. Dental comparison relies on the availability of good quality ante-mortem dental records to achieve a positive identification. Unfortunately, not all dentists keep good quality dental records, and this may hamper identification. These records are also subject to error (intentional or unintentional) during compilation.

One of the aims of this research project is to enhance identification methods used in Kelantan and Malaysia. Even though DNA analysis will continue to be used, there may still be a need for other latent evidence for comparison. Potential latent DNA evidence is usually sought from missing person's lists. This potentially overwhelming task could be reduced if there were a screening method available that used teeth to narrow down potential evidence. The main aim of dental evidence would be to provide putative identity, which would comprise information relating ethnicity, sex and age at the time of death. By establishing putative identity using dental evidence, costs and time related to DNA analysis would be reduced. The use of this method could also be extended for exclusion of identity, particularly in mass disaster situations. For example, in aviation disasters where the list of passengers and crew members are known (a so-

called closed disaster), screening methods could enhance the speed of the reconciliation process.

Dental record comparisons have become more limited in their application not just because of poor quality dental records. The big reduction in caries experience in Malaysian children due to effective preventative programs now presents a big challenge for forensic dentists. There are fewer carious and restored teeth available to be used in the comparison process. Assessment of dental variation (tooth morphology and size, and arch morphology) can offer an alternative identification method even though it might only lead to reconstructive identity.

Identification processes from the dental variation would not be affected by the quality of dental records, however, there is a need for reference standards of normal variation that can be used for specific populations, since the expression of dental features (tooth morphology and size, arch morphology and size) is known to vary between different ethnic groups. For example, Scott and Turner (1997) used 12 dental traits that characterized five subdivisions of mankind to assess the origin of an unknown skeletal sample. They compared total trait frequencies of the sample with frequencies from the 12 dental traits, and using an elimination process, were able to estimate the origin of the 'unknown' sample as being Western Eurasia. In particular, the lack of shovelling in the sample indicated that it could not have originated from East Asia, North Asia, or any Native American population. This process was continued for the other dental features until eventually they determined that the dental trait frequencies conformed most closely to Western Eurasian dental characteristics.

1.3 The use of teeth for identification

The use of teeth as identification tools can be traced back to the Roman era (AD 49) when Nero's mother identified the mutilated skull of Lollia Paulina from her dental characteristics (Keiser-Nielsen, 1984). In the modern era, teeth continue to play a significant role in identification in many disaster events, transport accidents, homicide investigations and wars.

One of the outstanding features of teeth is that they are robust and can survive decomposition and incineration, and thus are commonly found at disaster scenes. The enamel of the tooth is the strongest structure in the human body and is able to withstand heat up to approximately 1000^{0}C (Muller *et al.*, 1998). Teeth are also protected from direct heat by the tongue and thick facial and masticatory muscles. Posterior teeth have more chance of resisting heat effects than anterior teeth, thereby retaining their morphological appearance and restorations, which is important for comparison.

The size and shape of teeth results from a complex series of interactions between genes and the environment. The effects of the environment on genotype lead to individuality in teeth and the role of genes reflects ancestry or affinities of groups of people (Townsend *et al.*, 1994). The former has provided the basis for forensic investigations (identification and bite-mark analyses) whereas the latter has tended to occupy dental anthropologists interested in understanding the causes of human variation. It is well established that certain human populations e.g. Australian Aborigines (Brown *et al.,* 1980) tend to have larger teeth than others. Morphological studies have provided subdivisions of Mongoloid peoples into Sundadonts and Sinodonts (Turner, 1990). Sundadont people include South-East Asians who show smaller tooth size and simpler morphology than Sinodonts who live in Eastern and Northern Asia e.g. Japan, Taiwan, and northern parts of China. It has been suggested by Hanihara (1967), Mayhall and Saunders (1986) and Townsend *et al.* (1990) that combining several dental traits could enable different groups of people to be characterized. Three dental complexes have already been defined; namely Mongoloids (Hanihara, 1967), Caucasoids (Mayhall and Saunders, 1986) and Australians (Townsend *et al.*, 1990). Several researchers have successfully separated people according to their ancestry using dental data (Rosenzweig, 1970; Matis and Zwemer, 1971; Shields, 1996; Chiu and Donlon, 2000) and sex (Garn *et al.*, 1977; Garn *et al.*, 1979; Rao *et al.*, 1989; Lund and Mornstad, 1999). It, therefore, seems worthwhile to attempt to classify Malaysian populations according to their ancestry and sex using dental variation. It would appear that detailed studies of the morphology of teeth do have a place in forensic investigations especially when the dental data are studied with multivariate analyses such as Smith's mean measure of divergence, factor analysis and discriminant function analysis. Dahlberg (1963, 1985) suggested that biological data, when used in combination with appropriate statistical analysis, could provide a practical and usable alternative method for identification.

From both an historical point of view and from comparisons of physical characteristics (skin color and facial appearance), there would appear to be four main groups of Malaysians who live in Peninsula Malaysia: Malays, Chinese, Tamils and Jahais (Negritos). Following Turner's classification of people of East Asia using tooth morphology, Malays would be classified as Sundadonts, Chinese as Sinodonts, and Tamils as Caucasoids. Hanihara (1992) suggested that the Negritos should be classified as Proto-Sundadonts.

There is still only sparse information on the Malaysian dentition. Rusmah (1992) studied the frequency of Carabelli trait in Malaysians, but the study did not report frequencies for the separate ethnic groups. In addition to forensic and anthropological applications, details of dental

variation in Malaysians could also be useful for clinical management in orthodontic treatment planning, orthognathic surgery and genetic counseling.

Dental intervention techniques, designs and materials tend to be unique to the dentist and their country of origin (Whittaker, 1994). This can be very helpful for identification purposes especially when foreigners are involved in accidents. It is interesting to note some differences in dental techniques and materials found in Indonesians (from my own experience in dental clinics) who come to work in Malaysia. There is bridgework made of gold (without ceramic facings) on anterior teeth and bridgework made of denture acrylic. Another unique type of treatment which is not standard practice for Malaysian dentists is found with the use of cone-shaped plastic added to the fitting surface of an upper full denture to enhance retention.

Any excessive stress from the environment, e.g. disease, malnutrition or chemical insults, during the developmental period may also be manifested in the tooth structure. For example, tetracycline (a broad spectrum antibiotic) can lead to yellowish discoloration on specific teeth that are undergoing mineralization when it is consumed. This shows that teeth retain a record of events that occur during their development. Dental intervention during post-developmental stages also can be recorded throughout life. For example, missing premolars and well-aligned arches may indicate a person has received orthodontic treatment. In forensic situations where only one victim is known to have undergone orthodontic treatment such information could exclude the remainder of the victims.

Post-developmental changes in teeth, other than those due to caries and dental treatment, may include attrition, abrasion and erosion. Several distinctive features can be seen on teeth as a result of abrasion that may be work-related or habitual e.g. pipe smokers and hairdressers. These can have great forensic value as corroborative evidence and for identification by exclusion.

1.4 Population diversity in Malaysia

There are approximately 23 million people living in Malaysia, of whom 55% are Malays, 26% are Chinese, 7.7% are Tamils and less than 1% are Orang Asli, the latter being found only on the Peninsula of Malaysia.

The native people, or Orang Asli (Orang means people and Asli means pure), live in a new settlement area developed by the Malaysian Government through the Department of Orang Asli Affairs. The term Orang Asli is used to refer to 18 tribes from three larger groups totalling 92,523 people (Pusat Perkembangan Kurikulum, 1998; p.3). The three groups are Negritos, Senoi and Proto-Malays (Carey, 1976). Each of these groups has its own language and culture

and is distributed in different geographical areas of the Peninsula of Malaysia. For the purpose of this thesis, only Negritos are described. They are Negroid in appearance with dark brown skin, curly hair, round faces, flat noses and wide lips.

There are several opinions regarding the origins and history of Negritos on the Peninsula of Malaysia. It has been proposed that these people are the descendants of Australo-melanesians (Von Koenigswald, 1952). From skeletal (including teeth) and cultural remains, Von Koenigswald postulated that the Negritos represented the prehistoric Australo-melanesoid population in Malaya (Malaysia) and Indonesia, who were later replaced by Malays from Indonesia. The period of replacement was estimated to have occurred before the late Neolithic era.

Another view, proposed by Bellwood (1978), is that Mongoloid people migrated from China to the south, replacing people with Australoid features in West Malaysia. The only Australoid people who survived were those who lived in the secluded mountainous central areas, and it is these survivors who are known today as Negritos. An older view of the origin of the Orang Asli that has been disproved was the Pan-Negrito theory of Skeat and Blagden (1966). This theory suggested that all Orang Asli tribes came from Negrito origin and intermixed with the Malays.

Another view of the history of early Orang Asli settlement in Peninsula of Malaysia suggested two waves of migration (Pusat Perkembangan Kurikulum, 1998). It has been suggested that the first group came before 1304 AD from Indo-China and now reside in the northern part of Malaysian Peninsula. The second group of Orang Asli is believed to have come from Palembang, Sumatra and these people live in the southern part of Malaysian Peninsula. The Orang Asli lived side by side with the Malays in Tanah Melayu until the Sumatran Malays, who were very manipulative and oppressive towards the Orang Asli, arrived. This caused dissatisfaction among the Orang Asli resulting in a war called 'Perang Sangkel' or the Sangkel War. After this war, the Orang Asli removed themselves and lived in the jungle or remote areas where they remain to this day.

Dentan *et al.* (2001), in their review of archaeological evidence suggested that the Orang Asli were direct descendants of the Hoabinhians, with some mixture of Mon-Khmer speaking people through intermarriage. The current Negrito and Senoi dialects still retain some of the Mon-Khmer language (Evans, 1968).

The word Malay carries a mixture of biological and political implications. In the Federal Agreement, a Malay person is defined as a person who meets the following three criteria: he or she speaks the Malay language, practises Islam, and follows Malay customs. This means that

the term Malay includes those Malays from Java, Celebes, Sumatra and Pattani (Southern part of Thailand) and Malay-adopted Chinese children (Williams-Hunt, 1952). In the 1911 census, Javanese, Bugirese and Boyanese of Indonesian origin were grouped as Malays (Nagata, 1979). From a geographical perspective there is likely to have been more influence from Pattani in the Malays who live in Kelantan State. Historically, the Malays in the Peninsula of Malaysia are descendents of Proto-Malays who developed through an assimilation process with Chinese, Indian, Arabs and Thais. Their physical appearance is generally intermediate between Chinese and Indians (Figure 1.1).

Dentan *et al.* (2001) reviewed the origin and histories of Malays in West Malaysia and suggested that the Malays are of multiethnic origin, probably mainly from Austronesian-speaking traders, fishermen and pirates who settled in Peninsula Malaysia after 1000 BC. Other potential origin includes Arabs, Indians, Indonesian and admixture with the Orang Asli. What is clear from the different opinions is that the Malays are of mixed ethnic origin and that their terminology follows patrilineal lineage.

From a historical point of view, there were two important phases of migration of Chinese and Indians; pre-colonial and during British colonization. The major impact on the modern multiethnic Peninsula Malaysian population was from migration during British colonization in 19th and 20th centuries. During the pre-colonial era, the presence of Chinese and Indians in Tanah Melayu was mainly for trade. By 1848 very small number of Chinese and Indians chose to live in Tanah Melayu permanently.

The next important phase of migration occurred during the early 19th century. Increased need for cheap labour in tin mines, coffee and sugar cane plantations, and rubber estates during the post 1850s were the major reasons the British imported Chinese and Indian immigrants (Nagata, 1979; Zainuddin, 2003). Chinese immigrants came from south-east China; Kwangsi, Fukien and Kwangtung Provinces and Indian immigrants came mainly from South India.

Difficulties arose as there was a sex ratio imbalance within the immigrants (more males than females) (Nagata, 1979) and there was pressure for inter-racial marriages with locals to take place, however the prevalence of inter-racial marriages is not well documented. Even in today's Malaysian society, inter-racial marriages still occur between ethnic groups although there are cultural and religion barriers that limit the number.

In essence, the Malaysian population is composed of people with different geographic origins and obvious variations in physical characteristics. Using Montagu's (1960) mankind classification that considers skin color, form and character of the hair, form of the head and proportions of the body, there are Negroid (Negritos), Southern Mongoloids (Indo-Malays), Indo-

Dravidian Caucasoid (Indian), true Mongoloids (Chinese) and Pre-Dravidian Australoid (Orang Asli except the Negritos) resident in The Peninsula of Malaysia. Alternatively, if we used Bellwood's approach (Bellwood, 1978), Negritos would be classified as Australoids, Malays and Chinese as Mongoloids, and Indians as Caucasoids.

It is important to remember that any classification such as those above will never be perfect as there is no such thing as a "pure" race and, furthermore, the biological characteristics used are continuous in nature and subject to evolutionary forces (Relethford, 2000). The above classification can only be used as a means of grouping people with similarities in physical traits, cultures and geographical areas as ethnic groups rather than races (Montagu, 1960). It is very important to understand the limitations and problems that arise if one attempts to use such phenotype characteristics in forensic applications to estimate racial affiliation. For some characteristics, within-group variation may be larger than between-group variation, therefore, multivariate statistical analyses need to be utilised and prediction errors and success rates provided.

1.5 Forensic dentistry in Malaysia

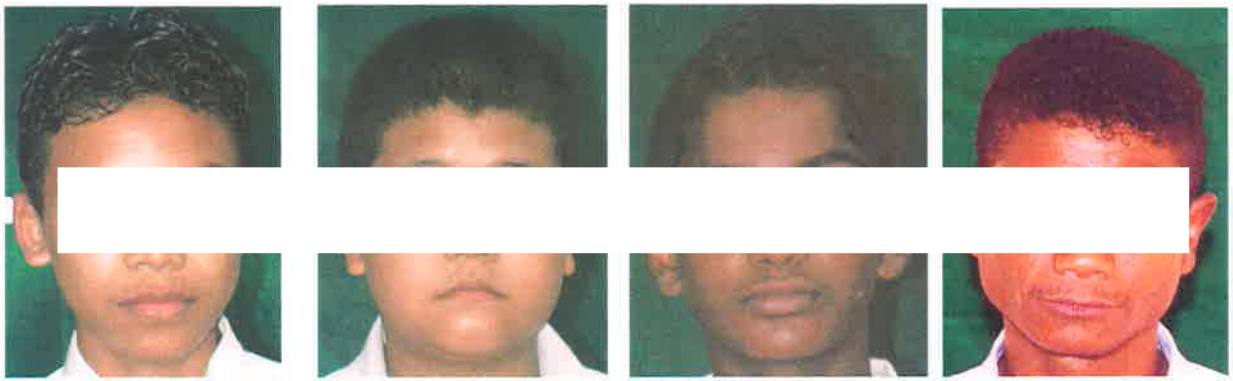
Forensic dentistry is a relatively new field in Malaysia compared to other dental disciplines. The first forensic odontologist completed his training in 1993. Major events that occurred not long after include the collapse of the Highland Tower in Kuala Lumpur and the MAS (Malaysian Airlines System) Fokker air crash in Tawau (Nambiar *et al.*, 1997). Unfortunately, the contribution of dental evidence to the identification process in these disasters was limited due to a lack of good quality dental records.

From a pilot study done in Kelantan, Malaysia (Khamis, 2004), the overall quality of dental records kept by dentists was not sufficient to confirm identification using dental comparisons. The study found that dentists' 'attitudes', standard of practice and lack of legislation about the maintenance of dental records were the most probable causes for these inadequacies. Improvement will take some time, so alternative dental methods for identification could be beneficial. The current practice by the Police Department in Kelantan is to rely heavily on DNA for identification purposes, even though the cost is high, because they have experienced poor outcomes in the past when dental comparisons have been used.

It is hoped to convince several key agencies in Kelantan, including the Malaysian Dental Council and the Malaysian Dental Association, that maintaining good quality dental records is important and that this should be addressed in the code of professional conduct and be taken seriously by all dentists.

For the time being it is impossible to persuade the police that forensic dentistry is an option for scientific identification when dental records are so poorly maintained. Hence, the aim of this project is to provide alternative methods of dental identification that are relatively easy to record and reliable, while at the same time trying to improve the current situation.

Figure 1.1 Facial appearance of Malays, Chinese, Indians and Jahai (Negrito)



Malays Chinese Indians Jahai (Negrito)

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Chapter 2 Literature review

2.1 Dental ontogeny

Studies of dental variation among different populations utilize knowledge of dental ontogeny resulting from the interaction between genotype and environment. It is important for dental anthropologists and odontologists to appreciate the normal developmental pathways of teeth, from undifferentiated cells until calcification determines final crown shape and size before eruption into the oral cavity. The complex pathways involve epithelial-mesenchymal signalling molecules that regulate morphogenesis and determine the position of specific teeth in "the right place and at the right time" (Tucker and Sharpe, 1998). Environmental insults during development may produce phenotypical variations, ranging from changes in ultrastructure to alterations in gross morphology depending on the severity of the disturbance. Since teeth attain their final crown size and shape before eruption, changes due to caries and other mechanical, physiological and chemical action can only occur once they have emerged in the oral cavity.

2.1.1 Odontogenesis, including recent molecular studies

Odontogenesis refers to the process of tooth development, which includes initiation, morphogenesis, differentiation and mineralization, root formation and eruption. These processes involve complex sequential and reciprocal interactions between the epithelial and mesenchymal tissues (Thesleff, 2003). The capability of cells to induce, be competent to respond to induction agents, and ultimately be capable of differentiating into specific functional cells is intrinsically linked to epithelial-mesenchymal signalling and regulation.

2.1.1.1 Morphodifferentiation and histodifferentiation

Before the various molecular regulators of dental development became known, descriptions of the developmental stages of teeth were based on examination of histological sections. In this section, dental developmental stages are described in terms of morphodifferentiation and histodifferentiation, that is shape changes of epithelium from thickening of primary epithelial band to bell shape, and cellular constituent changes, respectively.

Beginning in the sixth embryonic week, the oral epithelium thickens as a result of changes in the plane of cleavage of dividing cells within the oral epithelium. This thickened epithelium is called the primary epithelial band and gives rise to the dental lamina and vestibular

lamina (Ten Cate *et al.*, 2003). The process of tooth morphogenesis then proceeds from an initiation stage to budding of the dental lamina into the ectomesenchyme. At this stage, ectomesenchyme is concentrated around the epithelial bud.

The morphogenesis stage begins when the epithelial bud develops into a cap. The tooth germs start to become distinct morphologically, according to the future tooth type, i.e. incisor, canine or molar. Epithelial cells continue to proliferate and form a cap shape, called the enamel organ, with an intense condensation of ectomesenchyme underneath, which is called the dental papilla. The condensed ectomesenchyme surrounding the dental papilla and enamel organ is called the dental follicle and it gives rise to the supporting tissues of the tooth, e.g. cementum, alveolar bone and periodontal ligament. The transition from the cap to bell stage is marked by histodifferentiation of cells at the center of the enamel organ, giving rise to the star-shaped stellate reticulum. Another important structure is the enamel knot that is formed by clusters of non-dividing epithelial cells closely facing the ectomesenchyme (separated only by basal lamina). Enamel knots play an important role in cusp growth and morphogenesis, and mark the position of the future cusp tips.

As the tooth germ continues proliferating, its morphology changes from a cap to a bell shape. This is the stage when the tooth crown attains its shape and epithelial and mesenchymal cells differentiate into specific functional cells, namely ameloblasts and odontoblasts. The enamel organ consists of an outer dental (low cuboidal cells) and inner dental epithelium (short columnar cells). The folding of the inner dental epithelium (IDE) determines the shape of the tooth, i.e. whether it is unicusped or multicusped (Radlanski *et al.*, 1988). The action of folding is possibly due to physical interaction produced by differential cell mitosis within the IDE and the restricted area confined by dental follicle around the enamel organ (Butler, 1963). The IDE ceases to divide at the enamel knot, and its cells start to differentiate into ameloblasts. Away from the enamel knots, the internal dental epithelium continues to proliferate until the tooth crown attains its full size through completion of enamel formation.

This sequence of odontogenesis events refers to primary teeth. For permanent teeth, an identical sequence of events can be applied with a few exceptions (Ten Cate *et al.*, 2003). Permanent teeth, such as incisors, canines and premolars, begin development from the dental lamina on the lingual aspect of the primary tooth germ. Development of the permanent molars commences later when the jaw has developed and extended backwards. Further backward extension of the dental lamina gives rise to epithelial outgrowths from which the molar teeth normally develop.

2.1.1.2 Recent molecular studies of odontogenesis and determination of tooth shape

Before the era of molecular genetics, the genetic basis of tooth development was inferred from studies of dental phenotypes in twins (Townsend *et al.*, 1992), population variations in dental trait frequencies (Tratman, 1950; Bailit *et al.*, 1968; Bang and Hasund, 1972; Turner, 1990; Angel *et al.*, 1993; Scott and Turner, 1997), inheritance of dental traits in family studies (Townsend and Brown, 1978; Townsend, 1980), and studies of chromosomal anomalies (Townsend and Alvesalo, 1985a; Townsend and Alvesalo, 1985b; Townsend and Alvesalo, 1999). Building on these studies, understanding and knowledge of the genetic control of tooth development has improved considerably over the past decade with discoveries from studies of signalling molecules and transcriptor factors, with much of this work being done using knockout and transgenic mouse embryos. As Keranen *et al.* suggested "the gene expression patterns suggest that the odontogenic program consists of partially independent signalling cascades which define the exact location of the tooth germ, initiate epithelial budding, and transfer the odontogenic potential from the epithelium to the underlying mesenchyma" (Keranen *et al.*, 1999; p. 495). All tooth shapes and classes (e.g. incisors, premolars and molars) go through the same developmental pathways and comprise the same tissues (Stock *et al.*, 1997; Stock, 2001). In this section, various developmental pathways will be reviewed, including molecular regulation during the determination of tooth regions, localization of specific tooth identity and crown morphogenesis (to attain shape, including cusp growth), and formation of hard tissues.

During the initiation stage of dental development, the inductive capability lies in the ectoderm. As development proceeds from the initial determination of the oral-aboral axis (Tucker *et al.*, 1998) to the determination of tooth identity (dental patterning) disto-proximally along the dental lamina, ectomesenchyme maintains the ability to express signalling molecules and transcriptor factors which determine specific tooth classes, e.g. incisors (distal) and molars (proximal) (McCollum and Sharpe, 2001).

Several signalling families and transcriptor factors have been identified. The first mesenchymal markers identified during development are the *Lim-hox* homeobox genes; *Lhx6/7* which are induced by epithelial FGF8 (Grigoriou *et al.*, 1998). This establishes the oral region for future tooth development. Additionally, mesenchymal *Pax9* transcriptor factor establishes tooth bud formation in its caveat position (Neubuser *et al.*, 1997). Expression of *Pax9* is mediated by non-overlapping FGF8 stimulation and BMP2/4 inhibition. This antagonistic interaction between FGFs and BMPs also determines the expression of *Barx1,* which is restricted to proximal mesenchyme during tooth patterning.

Other important epithelial genes involved in determination of normal tooth position are the transcriptor factor *Pitx2* and the signalling molecule *Shh*. Initially they are expressed in a continuous band of the epithelium but later are restricted to the incisor and molar tooth germs within the dental lamina (Keranen *et al.*, 1999).

McCollum and Sharpe (2001) proposed an "odontogenic homeobox code" controlling determination of tooth patterning. According to this code, the murine jaw displays overlapping domains of expressed mesenchymal genes that determine tooth pattern (shape) in the correct proximo-distal position. *Barx1* and *Dlx1/2* domains overlap at presumptive molar regions while *Alx3* and *Msx1/2* overlap at presumptive incisor regions. It was noted also that expression of *Dlx1/2* and *Msx1/2* overlap to different degrees in the diastema area in mice, presumably corresponding to the coding for canine and premolars areas in humans.

After tooth regions and identity of individual teeth have been established, development proceeds with epithelial thickening and transient epithelial signalling centres (dental placodes) appearing. Ectodysplasin (Eda), a signalling molecule in the tumor necrosis factor (TNF) family, and Wnt are expressed in the oral epithelium, and mediate signals between the ectoderm of compartments regulating dental placode development via its mediators, *Edar* receptor and *Lef1,* respectively (Thesleff, 2003). Other molecules such as *activin βA* which is induced by FGF8, are important in development beyond the bud stage, except in the upper molars (Ferguson *et al.*, 1998). BMP4 induced via *Msx1* (Bei and Maas, 1998) operates reciprocally on epithelium (Jernvall and Thesleff, 2000) and regulates the formation of the dental placode (Thesleff, 2003). The dental placode contains four signalling molecules (BMP, FGF, SHH, WNT) which regulate the outgrowth of the dental lamina (budding) and condensation of mesenchymal cells surrounding the tooth bud. In addition, several other genes associated with signalling molecules are expressed; *p21* (a cyclin-dependent kinase inhibitor of cell proliferation), *Lef1, Msx2* and *Edar* (Ectodysplasin receptors). The dental placode formation marks the stage when inductive potential for tooth development is transferred to the mesenchyme (Thesleff, 2003).

The primary enamel knot shows many of the same genes from the four signalling families *Shh, Bmp2, Bmp4* and *Bmp7, Fgf3, Fgf4, Fgf9* and *Fgf20*, and *Wnt3, Wnt10a* and *Wnt10b* (Vaahtokari *et al.*, 1996; Thesleff, 2003) as those expressed in the dental placode. Signals from the enamel knot affect both epithelial and mesenchymal cells enabling the tooth to develop beyond the bud stage. This illustrates the reciprocal interactions between epithelial and mesenchymal expressed genes. *Fgf3* which is expressed only in mesenchyme and in the enamel knot is stimulated by FGFs expressed from the epithelium (Bei and Maas, 1998). FGFs and FGF receptors in non-enamel knot epithelium stimulate unequal epithelial growth around the

enamel knot that leads to epithelium folding at the early cap stage and subsequent tooth crown base formation (Jernvall *et al.*, 1994).

During the late cap stage, the primary enamel knot disappears via apoptosis (Vaahtokari *et al.*, 1996) followed by the appearance of secondary enamel knots at the position of future cusp tips in multi-cusp teeth. It is suggested that "the secondary enamel knots mark the first signs of a species-specific cusp pattern and their normal positioning is clearly important for this process to occur" (Cobourne and Sharpe, 2003; p.10).

Formation of secondary enamel knots is marked by restricted expression of *Fgf4* within the enamel knot, which is regulated by *Lef1* (Kratochwil *et al.*, 2002). *Fgf4* stimulates epithelial proliferation and at the same time induces BMP4 in the mesenchyme, which will inhibit further FGF4 signalling. Using a reaction-inhibition model, Jernvall and Thesleff (2000) explain this antagonistic mechanism with BMP4 diffusing faster than FGF4, thereby determining the spacing between secondary enamel knots. If the space is too close, cusp formation will be affected and the teeth may lose normal anatomical features suitable for occlusion and function. Despite the fact that interaction occurs between genes to maintain spaces between cusp tips, Townsend *et al.* (2003) found that intercuspal distances had lower heritability than crown dimensions. They suggested that epigenetic factors could play an important role in determining cusp tip location.

The whole process of tooth development uses the same signalling modules (largely) reiteratively (Jernvall and Thesleff, 2000; Thesleff, 2003). Thus, there are no specific genes for specific cusps. The activation of the first enamel knot and subsequent formation of secondary enamel knots follows a temporo-spatial trend, determining cusp position on the crown base (spatial) and cusp size (temporal knot initiation) (Jernvall and Jung, 2000).

The patterning cascade, as proposed by Jernvall and Jung (2000), suggests that the primary enamel knot establishes the crown base size which restricts the maximum number of cusps that can be formed. Tighter spacing between secondary enamel knots allows more cusps to form on a restricted size crown base than larger spacing, and shorter and smaller cusps are initiated later than taller cusps. Since the later developing cusps are subjected to cumulative variation from earlier formed cusps, they are susceptible to more selective pressures than larger earlier formed cusps. Therefore, their absence or presence and degree of expression tend to be highly variable (Butler, 1939).

The internal dental epithelium (IDE) continues to proliferate, except at the enamel knots, until the tooth crown attains its full size and enamel has been laid down. Once *p21* inhibits epithelial cells mitosis, evidence suggests that *Fgf9* (Kettunen *et al.*, 1998) and *Shh* (Jernvall and Thesleff, 2000) initiate IDE and mesenchymal cells to differentiate into ameloblasts and

odontoblasts, respectively. BMPs expressed in the IDE (Aberg *et al.*, 1997) and mesenchymal *Cbfa1* (Runx2) (D'Souza *et al.*, 1999; Aberg *et al.*, 2004) are also capable of stimulating mesenchymal cells (dental papilla) to differentiate into odontoblasts.

The processes of odontogenesis and amelogenesis require reciprocal induction between odontoblasts and ameloblasts (Ten Cate *et al.*, 2003). Amelogenin secreted by ameloblasts is believed to play a role in regulating cell signalling and mineral deposition. The tooth crown attains its final size when the crown calcification is completed at the cervical loop.

Understanding tooth ontogeny provides some working explanations about variation within the human dentition. The notion that variations in observed frequencies of dental traits between different populations reflects underlying differences in genotype is supported by the fact that molecular studies have shown genetic controls regulating tooth development. Earlier descriptive studies of frequencies of crown features, for example Carabelli trait, in different populations also link phenotype with genes (Kraus and Jordan, 1965).

Recent studies using mouse embryos have revealed that genetically-based signalling, especially in the enamel knot, mediates the duration and speed of mitotic activity of folding of the IDE that determines crown shape and size (Jernvall *et al.*, 1994; Vaahtokari *et al.*, 1996). Apoptosis or programmed cell death of the enamel knot may control the duration of mitotic activity, which restricts the crown base size (Jernvall and Jung, 2000). Another factor to consider is the spacing between secondary enamel knots. Larger crown base size and tighter spacing allows more cusps to form than larger spacing and smaller crown base size (Jernvall and Jung, 2000). Both factors may affect appearance or non-appearance of later-developing cusps and ridges/nodules in different populations with different genotypes. This understanding of the cellular and molecular basis of odontogenesis provides the rationale for selecting, for example, hypocone reduction on second molar teeth and cusp number on lower second molars (loss of hypoconulid) as traits to be used for population characterization. Both cusps are later-developing cusps, are normally small and short, and are highly variable.

Genetic studies of dental development have shown that some genes have pleiotropic effects, leading to associations in phenotypic expression within and between tooth families in the same jaw, as well as redundancy in actions that ensures teeth still develop according to a master plan despite environmental perturbations (Thesleff and Aberg, 1999; Sharpe, 2000; McCollum and Sharpe, 2001). There is also inter-arcade autonomy in tooth development programmes, as has been shown by the action of the *Dlx* transcriptor factor family (Thomas *et al.*, 1997). In the rest of this literature review, selected studies of dental variation, within and between populations will be reviewed to understand and link the nature and extent of dental

phenotypes with underlying genetic control leading to forensic and dental anthropological applications.

2.1.2 Environmental influences on teeth

Environmental influences can affect the dentition during pre-natal, perinatal and post-natal periods. By comparing the type of tooth affected and the location of the effects produced, the timing of insults can be estimated (Taji *et al.*, 2000). As an example, primary tooth crowns normally begin to calcify from 12.5 weeks in utero for primary incisors and molars to 20 weeks in utero for primary canines and all crown formation is completed at 11 months post-natal (Kraus and Jordan, 1965). Insults that occur at specific times of tooth formation will be recorded as lesions on specific locations of the tooth structure (Taji *et al.*, 2000). Lesions, depending on whether they are localized or systemic, will be recorded on a tooth or group of teeth, and they may be unilateral or bilateral. Thus, primary teeth represent a good model for evaluating the effects of pre-natal, peri-natal and early post-natal environmental influences.

A variety of phenotypic variations may result from environmental effects on the dentition. These may range from fluctuating asymmetry in crown size and shape, crown defects ranging from opacities of enamel (reflecting the quality of the enamel matrix laid down) and hypoplastic lesions, to alterations in crown shape and size, depending on the nature and severity of cumulative environmental insults, timing of insults and the buffering capability of the host. In this section, the latter three factors will be reviewed. Fluctuating asymmetry as an indicator of environmental insults/stress, will be covered in brief in section 2.6.

There are several environmental factors leading to dental defects that have been reported from epidemiological and clinical studies in humans and also in experimental samples. Environment factors can be described as being local or systemic. Local factors usually produce localized defects. It is suggested that direct trauma to the ameloblasts during matrix formation may cause localized defects on one tooth or a few adjacent teeth. The appearance of the defect depends on the developmental stage when the trauma occurred. Opaque enamel results from trauma during the later maturation phase of amelogenesis whereas trauma during matrix formation results in hypoplastic defects (Seow, 1991). Examples of local conditions giving rise to hypoplastic enamel include microorganisms from an infected primary tooth (McCormack and Filostat, 1967), and physical trauma, such as direct pressure from the endotracheal tube on the alveolar ridge may cause trauma to the embedded developing primary tooth germ in a premature baby (Moylan *et al.*, 1980).

Systemic factors such as birth trauma, low birth weight, prematurity, infection, drugs and chemicals, nutritional disorders, and metabolic diseases have all been reported to contribute to enamel defects. During normal birth, changes from the intrauterine to the extrauterine environment may cause subclinical enamel hypoplasia, known as the neonatal line (Schour, 1936). The presence of the neonatal line may be exaggerated if stressful conditions surround the birth for example multiple pregnancy or prolonged labour (Funakoshi *et al.*, 1981)

Severe infections can cause defects during amelogenesis. The possible mechanisms include direct injury to ameloblasts by microorganisms (Seow, 1991) and ameloblastic and odontoblastic derangement due to elevated body temperature (as in maternal pyrexia) (Kreshover and Clough, 1953). As an example, congenital rubella and syphilis (Cohen *et al.*, 1977) can affect both primary and permanent teeth.

Excessive ingestion of fluoride may cause enamel mottling. Both permanent and primary teeth can be affected, with permanent teeth affected more severely (Smith and Smith, 1935). DenBesten *et al.* (2002) studied the effects of fluoride on dental enamel matrix proteinase in the rat. Under normal conditions, five to 10 μM of fluoride can affect the amount of active proteinase during the maturation stage, however, at lower pH, two μM can reduce matrix metalloproteinase-20 (MMP-20) hydrolysis activity. As a result, amelogenin removal from the matrix was delayed leading to disturbance in enamel mineralization.

Malnutrition and metabolic diseases have also been reported to cause enamel defects. Metabolic disease associated with renal or liver malfunction can cause derangement of vitamin D and calcium metabolism (Shusterman and Fellers, 1969). Children with hypocalcemia tend to show a higher prevalence of hypoplasia than normal, 73% to 3% respectively (Seow *et al.*, 1984).

As mentioned above, different types of environmental insults can produce changes in micromorphology and ultrastructure of dental crowns (Moller, 1967). Other researchers have provided evidence of gross morphological changes, such as tooth size, pits and fissures, and cusp height (Paynter and Grainger, 1956; Garn *et al.*, 1979b). Tooth size has been shown to diminish (smaller tooth size) and more towards simplification (shallow pits and fissures) in rats with high phosphate, 12 ppm fluoride (given during pregnancy and lactation), and vitamin A deficiency (Paynter and Grainger, 1956). In support of these findings, Moller suggested, "...in addition to genetic factors, a nutritionally adequate diet (or other influence of microelements) might be necessary for the formation of harmoniously structured and well-mineralized enamel and dentin". (Moller, 1967; p.926).

After a tooth has erupted into the oral cavity, changes in its crown dimensions and morphology are mainly due to wear, pathological changes and dental treatment, or as a result of deliberate mutilation as seen in traditional, cultural and ritual practices.

Tooth wear can be attributed to attrition, abrasion and erosion whether acting independently or in combination (Bartlett, 2005). Attrition, caused by tooth-tooth contact, for example due to bruxism (Milosevic *et al.*, 1997) tends to leave polished surfaces or wear facets on opposing teeth. Abrasion is caused by foreign particles, e.g. fibre rich food acting on tooth surfaces during mastication or vigorous tooth-brushing with the abrasive toothpaste. Erosion caused by action of chemical substances e.g. acidic drinks (Jarvinen *et al.*, 1991), hydrochloric acid regurgitated from the stomach in gastro-oesophageal reflux disease (Moazzez *et al.*, 2004), produces a 'scooped out' appearance due to the higher rate of erosion on softer tissue (dentine) than harder tissue (enamel). Diagnosing the different causes of tooth wear, however, is difficult as the result is rarely the product of one single factor (Bartlett, 2005).

Dental treatment for pathological lesions such as caries varies in terms of technique, materials and standard of workmanship between countries, due to both dental training and legislation. It can be possible to gain a clue as to the origin of the dentist who has produced the treatment or the individual's nationality by analyzing the interventionist dental treatment.

More extreme environmental effects on the dentition can be seen in certain aboriginal tribes. Wilson *et al.* (1992) reviewed traditional, ritual and cultural practices in several populations from different continents. The practices vary from tooth mutilation, tooth avulsion, and tooth crown mutilation resulting in modification of the dental crown by chipping, dyeing on the surface of the crown and adornment of the crown with inlays.

2.2 Patterns of variability in the human dentition

Human teeth are composed of four morphological classes; incisors, canines, premolars and molars, with each having a similar shape and a specific group function. In this section, patterns of variability within the morphological classes will be discussed. As has been discussed in Section 2.1, odontogenesis follows a programmed genetic control but at the same time tooth germs can be exposed to environmental disturbances. The final phenotype of tooth shape and size is dependent on the level of developmental stress and the capacity of the individual to buffer stress to maintain homeostasis.

Two theories have been proposed to explain patterns of tooth variability within morphological classes. The first, quite widely received theory, was based on observation of the dentitions of Cenozoic mammals (Butler, 1939) and was adapted to explain variability in the

human dentition by Dahlberg (1945). This theory, known as the Field Theory, proposes that the most mesial tooth in each morphological class possesses more stability than the distal ones, resulting in the tooth furtherest from the 'key' mesial tooth having the least concentration of field substances. As a consequence, there is more variability in the size of the distal teeth in each class, e.g. lateral incisors > central incisors (I2>I1), canine (C), second premolars > first premolars (P2>P1) and third molar > second molar > first molar (M3>M2>M1) (Dahlberg, 1945). Evidence to support morphogenetic fields within the dentition has come from population studies based on coefficients of variation (CV) of measurements, asymmetry, heritabilities, frequencies of occurrence for dental traits, tooth size and morphology inter-relationships (Townsend and Brown, 1981b), molecular experimental studies (Ten Cate *et al.*, 2003) and multivariate analyses (Lombardi, 1978; Harris and Bailit, 1988). Field theory application from studies of asymmetry, association between dental traits and heritability will be discussed in later sections.

The coefficient of variability (CV) is calculated as the ratio of the standard deviation to the mean, expressed as a percentage. Thus, CV values enable comparisons of variability within the dentition. Townsend and Brown (1981b) reported dimensional variability similar to Dahlberg (1945) except variability in lower central incisor (LI1) was found to be larger than in lower lateral incisor (LI2). Generally, the first molar is the least variable tooth in the molar series. In other fields, for example premolars and incisors, the key tooth is not always the least variable. Hanihara (1976), Perzigian (1976), Townsend and Brown (1979), Harris and Nweeia (1980a) and Kieser *et al.* (1985) found some patterns of variability in their samples that did not agree with those described by Dahlberg (1945) and Townsend and Brown (1981b). Hanihara (1976) compared CV values among six populations and found a reversed pattern of variability in the upper and lower premolars in male Australian Aboriginals, male and female Japanese and Ainu males. A similar finding was reported for the lower incisors in Ainu, American Caucasians and American Negroes. In Australian Aborigines only was the reverse pattern found in the molar series. A similar reversed pattern was also observed for Indian Knoll upper premolars (Perzigian, 1976). Townsend and Brown (1979) suggested CV values in the premolar series did not show a clear pattern consistent with field theory. A rare reversed patterning was observed in Ticuna males (BL) and females (MD and BL) for upper incisors (Harris and Nweeia, 1980a) and for the MD dimension of upper incisors in South African males (Kieser *et al.*, 1985). Clearer evidence of morphogenetic fields has come from multivariate analyses (Lombardi, 1978). Using factor analysis, Lombardi (1978) found four factors describing tooth size and shape variation consistent with morphogenetic Field Theory. Harris

and Bailit (1988) also found specific factors consistent with morphogenetic gradients determining tooth size variability using principal components analysis in a large Melanesian sample.

Reversed or inconsistent patterns of field gradient have also been observed for morphological traits. Townsend *et al.* (1990) found the pattern of occurrence of entoconulid expression in Australian Aborigines did not follow the morphogenetic gradient M1>M2>M3, but an inconsistent pattern of M3>M1>M2, even though the greatest genetic influence is thought to be on M1. In occurrence and expression of metaconule from the same sample, Townsend *et al.* (1986) also found a reversed morphogenetic gradient; M3>M2>M1. The key tooth, (i.e. recording the highest frequencies) for metaconule in this sample was M3. Earlier, Harris and Bailit (1980) showed that the frequency of metaconule occurrence in Melanesians was the highest in M1 and lowest in M3, and they concluded that M1 was the key tooth for this trait, although, mean size and variability of the trait increased distally.

Another theory proposed to describe variability within the dentition is the Clonal Theory (Osborn, 1978). Clonal Theory differs from Field Theory in several ways (Osborn, 1978; p. 173):

1. In a field model it is axiomatic that all primordia are equivalent: if they were different there would be no necessity for a field substance. In contrast, it is axiomatic in the clone model that all primordia are different. As soon as it has been initiated the final shape of a primordium has been largely determined.
2. In a field model the shape into which a structure develops is controlled from outside. In a clone model it is self-generated from within. For field models, shape is induced; for the clone model, shape is intrinsic.
3. In field models a primary gradient (of field substances) induces the development of a matching secondary gradient (of shapes). In the clone model gradients are the result of growth: until growth starts the gradient cannot exist and when growth stops the gradient ends. Growth "unfolds" the gradient.

Kieser (1984) supported clonal theory to account for his observation of Carabelli trait in mixed and permanent dentitions of 240 samples of South African whites. Using the same sample, Kieser *et al.* (1985) measured tooth size and the pattern of coefficients of variation obtained for premolars, which he concluded also, supported the Clonal Theory.

Both theories, are supported by molecular studies. The difference between the two can be related to the timing of tooth development. At the early stage of tooth development, recombinant experiments on mice have shown that the inductive power to determine tooth

patterning is acquired from the oral epithelium (Clone Theory) whereas after E10.5 the induction power has been transferred to the ectomesenchyme (Field Theory) (Ten Cate *et al.*, 2003). Butler (2001) also commented that, in addition to field theory, clonal theory was able to give a better explanation for distal development in the dentition. Sofaer *et al.* (1972a) also observed that the longer soft tissue developmental period in distal teeth provides more opportunity for influence from environmental factors.

2.3 Associations between different dental traits

Studies of inter-trait associations are important to describe the underlying biological mechanisms controlling tooth development. In addition, information derived from these studies can enable researchers to select traits that are independent of each other and to justify using both metric and non-metric traits to characterize and compare populations.

Issues for consideration include whether associations exist between different traits within the same tooth, between tooth groups for the same trait, and between different traits and tooth groups. When an association exists between two traits it suggests that both traits share a common developmental determination or genetic dependency. The pattern of expression of the traits has often been shown to follow Field Theory (Dahlberg, 1945; Townsend and Brown, 1981b).

Researchers have studied the relationships of several different dental traits in the lower molars. For example, Garn *et al.* (1966a) found that groove patterning was expressed independently from cusp number and from mesio-distal tooth size in the lower first molars of Ohio Caucasians. These researchers also concluded that tooth size was associated with cusp number. Similar trends between tooth size and cusp number in lower second and third molars were reported by Dahlberg (1961). Lombardi (1975) compared mesiodistal and buccolingual diameters of lower first molars with and without a Y-groove pattern and found that molars with Y-groove patterns were significantly larger than those without. In another morphological study of lower first molars in Icelandic children, Axelsson and Kirveskari (1982) found small negative correlations between cusp number and entoconulid expression and small positive correlations between cusp number and groove pattern, as well as between groove pattern and deflecting wrinkle expression.

Scott (1977a) studied shovel trait associations between maxillary and mandibular incisors, (e.g. upper central incisor (UI1)-lower central incisor (LI1), upper lateral incisor (UI2)-lower lateral incisor (LI2)) and within-jaw comparisons (e.g. UI1-UI2), in 1251 American Indians and 113 American whites. He found moderate and statistically significant correlations in 56 out of

66 comparisons. For the LI1-LI2 comparisons, the correlation coefficient was higher (r=0.77). The trend of associations followed Butler's field theory (Butler, 1939) with shovelling expression between the upper lateral incisor (UI2) displaying smaller correlation coefficient values (more variable) than those between upper central incisors (UI1). Based on these findings, the author postulated that there was a broad field of shovelling growth in the incisor and canine regions.

There are conflicting results in the pattern of inter-trait associations between traits, and within and between tooth groups. Reid *et al.* (1991) found that the areas of all four main cusps (protocone, paracone, metacone and hypocone) of the upper first molar were positively associated with expression of Carabelli trait. Lombardi (1975) also reported similar results, finding that upper first molars with a Carabelli cusp had significantly larger mesio-distal and bucco-lingual diameters. Garn *et al.* (1966d) showed that Carabelli trait was independent of mesio-distal (MD) tooth size of the upper first molar, of hypodontia of the lower third molar and of cusp number and groove pattern of the lower first molar. In a sample of 202 Egyptians Motayam *et al.* (1985) found low (r=0.2-0.3) insignificant correlations between Carabelli trait and protostylid expression, when both traits were scored as either present or absent. In another study, Scott (1978) used a nine-grade scale to describe Carabelli trait and a six-grade scale for protostylid in 676 Southwest American Indians. He found significant correlations in all groups except the Hopi Oraibi sample (phi value=0.02). He used both Kendall's tau for ranked-scale data and phi for dichotomous data. Even though most of the correlations were significant, generally values of coefficients in these six groups indicated only weak correlations from 0.18-0.40 (Kendall's tau) and 0.02-0.33 using phi Scott's findings, therefore, were not much different from the results reported for the Egyptian sample of Motayam. Scott (1979) studied 800 dentitions from six groups of Southwest Indians to assess the association between hypocone and Carabelli trait expression. Using Kendall's tau he found positive and significant associations for each of the four comparisons; hypocone on the upper first molar (UM1) with Carabelli UM1, hypocone UM1 with Carabelli of the upper second molar (UM2), hypocone UM2 with Carabelli UM1 and hypocone UM2 with Carabelli UM2, except in a few comparisons. Once again the coefficients were generally weak; mean tau values from six samples being 0.28, 0.13, 0.29 and 0.14 for each of the four comparisons. The results also indicated that the expression of Carabelli trait on upper second molars was less stable than its expression on upper first molars.

Kieser and Becker (1989) discovered independent relationships in Negroes, Caucasoids and Amerindians between upper first molar size (MD and BL dimensions) and Carabelli trait (except in Amerindians' males), as well as canine mesio-distal size and distal accessory ridge expression (DAR). They also found that DAR expression was independent from Carabelli trait

expression. They hypothesized that metric and non-metric integration is a distinctive feature of incisors, but not of canine or post-canine teeth. An earlier study by Lombardi (1975) provided results consistent with this hypothesis; namely significant associations between shovelling and mesiodistal diameters of upper central and lateral incisors.

Sofaer *et al.* (1972a) discovered generally low positive correlations between dental traits, with a range of coefficients from 0.01-0.35. The traits included cusp number of upper second and third molars, cusp number of lower first (LM1) and second molars (LM2), shovelling of upper central and lateral incisors, Carabelli trait of upper first and second molars, and groove pattern of LM1 and LM2. Only correlations between groove pattern and cusp number of lower first molars were consistently positive and significant. All within-trait correlations between teeth of the same class were positive and significant, with higher coefficients for shovelling and Carabelli, 0.67 and 0.65 respectively. In eight out of 10 comparisons, positive and significant correlations were reported between tooth size and tooth morphology, however the actual values of coefficients were not presented. From this study the author suggested that there was "a degree of common basis for variation of each character within a tooth class", which again supported the field theory (Butler, 1939; Dahlberg, 1945).

Moorrees and Reed (1964) studied odontometric inter-relationships and found that values of correlation coefficients of single teeth between and within tooth groups were in the range of 0.26-0.67 and 0.21-0.76 in primary and permanent teeth, respectively. It was also shown that within-group coefficients were the highest, ranging from 0.45 to 0.76. The mesial tooth was found to be associated with higher coefficients than less stable teeth from the same tooth group. Garn *et al.* (1965c) found similar results with mean correlations for mesial teeth being always larger than correlations in distal teeth except for lower lateral incisors. Both of these odontometric results were consistent with previous morphological studies that supported the Field Theory (Butler, 1939; Dahlberg, 1945). Once again, overall correlations were low to moderate, ranging from 0.39 to 0.60.

Garn *et al.* (1968a) found positive, low to moderate correlations between mesio-distal (MD) and bucco-lingual (BL) crown diameters. On average, however, only 26% (r=0.55) of the variance in MD dimensions could be explained by values in BL dimensions. The authors concluded that there was "autonomy" (independence) between both of these dental crown measurements.

In summary, although significant correlations have been reported between teeth for both metric and non-metric traits, and also between some metric and non-metric variables, the values of coefficients have been low to moderate. The strongest correlations reported have been those

between traits within the same tooth class. Therefore, it would appear to be justifiable, from both statistical and biological viewpoints, to use metric (tooth type) data derived from permanent teeth (except third molars) and non-metric (morphological) data derived from the mesial teeth within tooth classes to characterise dental variation within human populations and to make comparisons between them. An exception would be for traits reflecting reduction or simplification of crown form, e.g. hypocone reduction in upper second molar, cusp number in lower second molar and Y-groove pattern on lower second molar, where the distal tooth within a class might be used.

The pattern of phenotypic expressions that has been reported within and between teeth for various metric and non-metric traits suggests the existence of underlying common developmental factors. The concepts of morphogenetic fields within the dentition that have been found on observed variations are now being supported by molecular studies that are confirming the existence of odontogenic homeobox genes that determine tooth patterning.

2.4 Genetic studies of the human dentition

Researchers have emphasised the importance of understanding the role of genetic influences on dental traits and tooth size for application in forensic odontology, population variation and human evolution. The concept of identification relies on the individuality of the dentition which comprises certain dental phenotypes observed more frequently in one population than another as a result of genetic interaction with the environment (Dahlberg, 1957). This means that dental phenotypes studied must have substantial genetic attribution to ensure meaningful biological inter-relationships rather than just being counting 'lumps' and 'bumps' on tooth surfaces. As stressed by Townsend *et al.* (1994; p. 37) "a fundamental assumption of studies of human affinities and migratory pattern based on dental crown features is that the traits are under strong genetic influence or, at least, that the environments affecting dental development are similar world-wide". Several other researchers have expressed similar opinions, emphasising the importance of obtaining maximum knowledge of the genetic contribution to dental morphology and size before population variation can be meaningfully assessed (Sofaer *et al.*, 1972b; Berry, 1976; Berry, 1978; Falk and Corruccini, 1982; Mayhall, 1999).

Early researchers used univariate tooth-by-tooth comparisons to elucidate genetic contributions to observed variability. Horowitz *et al.* (1958) conducted twin studies using upper and lower incisors and canines of monozygotic (MZ) and dizygotic (DZ) twins of both sexes. They analysed genetic contribution to crown size variation by assessing the F-ratio for intra-pair

mean difference between twins. Small mean intra-pair differences in twins and significant F-ratios between MZ and DZ twin pairs implied strong genetic factors. They suggested that there was a strong genetic influence affecting variability in mesiodistal crown size of all incisors and the right mandibular canine, however, low heritability was found for the other three canines. They compared their findings with field theory and suggested that "...limited genetic variability of the canine observed in this study is compatible with Dahlberg's hypothesis of a comparatively slow rate of evolutionary change, or 'stability' in this tooth" (Horowitz *et al.*, 1958; p. 92). In my opinion the explanation given is rather superficial, as it is difficult to understand why one tooth would display a different result from the others, except perhaps due to sampling effects. If this were the case, the results for all teeth would need to be viewed with some caution. Furthermore, although the authors acknowledged that environmental factors were likely to be involved there was no quantification of their role, perhaps due to the absence of computer technology for multivariate analyses.

Garn *et al.* (1965b) suggested an X-linked mode of inheritance for tooth size determination. This finding was based on the pattern of correlation coefficients between siblings: sister-sister > brother-brother > brother-sister correlations with averages of 0.64, 0.38 and 0.21 respectively. Garn *et al.* (1965d) observed tooth size and development within families and in twins, and found evidence that both X- and Y-chromosomes mediated size and development. The authors estimated that 90% of variance was attributable to genetic factors. A similar opinion was provided by Lundstrom (1977) who concluded that tooth size variation conformed with a theoretical pattern of X-linkage without dominant effect. Hanihara and Ueda (1979) disputed X-linked inheritance and proposed a polygenic model of inheritance. Using several multivariate analyses they were able to show that the mesiodistal tooth size of 170 F1 hybrids of Japanese woman with male American soldiers was intermediate between the parental populations. Researchers later confirmed the role of both sex chromosomes, X and Y, on tooth crown development based on studies of individuals with various chromosomal abnormalities (Alvesalo and Tammisalo, 1981; Alvesalo and Tammisalo, 1985; Alvesalo *et al.*, 1987) and also laboratory findings (Lau *et al.*, 1989). The differential effects of the sex chromosomes on dentine and enamel appear to give rise to the sexual dimorphism observed in tooth crown size. In addition to sex chromosome involvement in determination of tooth size, odontometric studies in individuals with autosomal chromosome abnormalities, such as Down syndrome, have revealed disturbances in their phenotype, with permanent tooth size being smaller than in unaffected individuals (Barden, 1980b). The genetic mechanism is unclear but it

is believed that deceleration of mitotic activity may cause the retarded phenotype (Barden, 1980b; Townsend, 1983; Peretz *et al.*, 1996).

Garn *et al.* (1968b) examined genetic distance using crown profile patterns among 14 unrelated normal populations, twins, sibling-sibling, and parent-child. Their results suggested a strong genetic contribution. Alvesalo and Tigerstedt (1974) found high heritability in tooth size in full siblings with average values of 0.59. The average heritability for mesiodistal diameter was 0.54, the value for buccolingual diameters was higher, at 0.67. They emphasized environmental (non-genetic) factors affecting phenotypic variability and indicated that the larger the component of environmental contribution, the greater the phenotypic variability. Genetic contributions to tooth size determination were further investigated by Potter *et al.* (1976) who suggested independent genetic determinants affecting the maxillary and mandibular teeth, but similar genetic control for homologous right and left teeth.

Townsend and Brown (1978) partitioned tooth size variability into four variance components; between sides, between fathers, between mothers and between off-spring. The heritability was estimated at 0.63±0.30 (MD) and 0.66±0.31 (BL) for half siblings, and 0.72±0.08 (MD) and 0.81±0.08 (BL) for full siblings. The overall additive genetic effect was 64% and common environment contributed 6% to the observed tooth size variability, while the remaining 30% was attributed to the within family environment component of variance.

In a recent application of genetic modeling methods, Dempsey *et al.* (1995) have quantified variation due to additive genetic and unique environmental effects except on the incisors in twins. Their estimations of heritability come close to 90%. Research using all teeth (except the third molars) showed that the heritability estimates were 0.56-0.91 for MD diameter and 0.61-0.92 for BL diameter (Dempsey and Townsend, 2001). The authors also emphasized the environmental effects on the tooth size, namely unique environment effects ranged from 8-29% and common environment effects on the upper first molar accounted for 22-27% of observed variation.

While continuous data like tooth size generally fit well with a polygenic model which shows a normal distribution (Mueller and Young, 2002), morphological dental traits, which are discrete in nature and when present show graded expression, tend to follow a 'quasi-continuous' variation model (Harris, 1977). Quasi-continuous variation means the underlying genetic basis is assumed to be associated with superimposed thresholds (Gruneberg, 1952). Traits with distribution below the threshold would not be detected phenotypically.

Several studies using twins of known zygosity and serology analysis have supported the premise that morphological traits have a strong genetic basis. Lundstrom (1963) reached

94.4% correct classification using 124 pairs of twins. He used cusp number, fissure-arrangements, crown forms and palatal surface of incisors and canines as discordance criteria. Wood and Green (1969) obtained lower classification rates, 86.2% and 83.9% for homolateral right and left, respectively. They used seven traits on only one tooth type, the lower second right and left premolar. Another group found a high level of correct classification at 97.5% (Townsend *et al.*, 1988). They utilized several criteria including four general features: anterior crown form, labial and palatal surface, posterior occlusal crown features and crown form, molar cusp number and Carabelli trait. There seems to be a trend where high reliability involves use of more tooth types (Townsend *et al.*, 1988). The dissimilarities are subtle, yet it can be inferred that there is environmental interaction with genetic factors.

The second group of studies observed frequency differences across different populations using both normal populations and twins. Ludwig (1957) concluded that tooth morphology is inherited and frequencies vary across four major world populations. He concentrated the study on only one tooth, the lower second premolar, and scored seven traits including the occlusal ridges of the buccal cusp, the median occlusal ridge of the buccal cusp, the relative position of the lingual cusp, the number of lingual cusps, the independence of the lingual cusp, the position of multiple lingual cusps, and the sagittal sulcus. However, this study did not quantify heritability of the traits.

The third type of study involved correlations within family members and twins, and estimations of heritability and environmental factors. Sofaer *et al.* (1972a) studied family resemblances in several dental traits: shovel shape on the upper central and lateral incisors; Carabelli on the upper first and second molars; groove pattern on the lower first and second molars; cusp number on the upper second and third molars; and cusp number on the lower first and second molar. They suggested that Carabelli trait on the upper first molar and groove pattern of the lower first molar were good ethnic discriminators due to their relatively high resemblance and independency. Another important finding was that traits on the later developing teeth (distal member of tooth class) tended to show large phenotypic variability, leading the authors to suggest that the mesial tooth received larger additive genetic effects while the distal member of the tooth class received larger environmental effects. Berry (1978) studied 91 MZ and 89 DZ Caucasian twin pairs and 122 Caucasian families from Liverpool. Forty five 'minor crown variants' (the term used by the author to refer to her dental morphological traits) were initially utilized in twins for concordance studies but for methodological reasons only nine individual variants were used for correlation studies within families. The author concluded that the results supported multifactorial influence with strong

genetic control and some interaction with environmental factors. She suggested that crown morphology was useful for anthropological studies. Townsend and Brown (1981a) tested correlations between siblings of individuals affected with Carabelli trait with siblings from the general population. They found low heritability for Carabelli trait suggesting substantial environmental factors influencing Carabelli trait variability. Biggerstaff (1973) also found a low degree of heritability of Carabelli trait based on percentages of concordances from a fairly large number of twins.

In contrast, other researchers have reported high genetic contributions to Carabelli trait determination. Skrinjaric *et al.* (1985) reported high heritability estimates for Carabelli in 95 pairs of twins. There were two versions of results: using individual count the estimate was 91%, while analyses on homologous side revealed 84% genetic contribution to Carabelli trait determination. Kieser (1984) reported that high correlation of Carabelli trait expression on the deciduous second molar with the upper first permanent molar was suggestive of high genetic contribution. Pinkerton *et al.* (1999) suggested strong genetic contribution in the expression of Carabelli trait in Australian twins. Townsend and Martin (1992) made full use of multivariate genetic analyses to search for the best model to explain the relative contributions from genetic and environment factors. The heritability was estimated at around 90% which was close to the estimation by Skrinjaric *et al.* (1985).

There have been several opinions offered regarding the mode of inheritance. Some researchers have suggested a polygenic multifactorial mode while others that inheritance followed Mendelian theory and the existence of major locus.

Townsend and Brown (1981a) indicated that Carabelli trait fits well with the polygenic mode of inheritance and from the trend of polychoric correlations, Pinkerton *et al.* (1999) suggested non-additive genetics may also play some role in the variation of Carabelli trait. Using multivariate genetic modeling analyses, Townsend and Martin (1992) found that additive genetic effects, general and specific environmental mechanisms fit well with the genetic model. Kolakowski *et al.* (1980) also suggested major gene involvement in Carabelli trait determination using 358 families from the Solomon Islands of Bougainville and Malaita.

Portin and Alvesalo (1974) found the mode of inheritance of shovel trait to be a single intermediate autosomal gene and did not support sex-linked inheritance for their sibling-sibling comparison, but they did not rule out the possibility that the polygenic model was also involved. Blanco and Chakraborty (1976) indicated that 68% of shovelling total variability could be attributed to additive genetic effects. In addition, they suggested that there was no evidence to support dominance effects since the sibling-sibling correlations did not differ from parent-

offspring correlations. In contrast, Sofaer *et al.* (1972a) proposed that the traits were polygenic with possible dominant effects.

Harris and Bailit (1980) studied large numbers of related individuals from 315 families from Melanesia. Several important findings were revealed from this research. Firstly, familial analysis of the metaconule did not support a simple mode of inheritance but was consistent with a quasi-continuous model. Secondly, the heritability estimates were 65% with weak evidence of sex-linked inheritance and thirdly, the upper first molar was found to receive high additive genetic effects which make the metaconule on the upper first molar suitable for use in population studies.

Nichol (1989) studied the mode of inheritance of a set of 20 morphological crown variants. The majority of traits were found to have major genetic involvement and few showed evidence of a polygenic mode of inheritance. Eight dental traits: shovelling on upper incisors, interruption grooves of UI2, incisor and canine double shovelling, Carabelli trait of UM1, lingual cusp number on the lower premolars, hypoconulid of LM1 and LM2, and cusp 7 have been identified to be influenced by a dominant allele, while hypocone of UM1 and UM2, and the transverse ridge of the lower premolars by a recessive allele. The groove pattern of LM1 and LM2 and the deflecting wrinkle of LM1 showed evidence of a polygenic model of inheritance, while labial convexity of UI1 and UI2, metaconule UM1, cusp 6 of LM1 and LM2, protostylid of LM1 and LM2, winging UI1, distal accessory ridge require further analyses. The authors also stressed the environmental factors affecting dental trait expression since using a polygenic model the heritability was found to be around 36% only. Importantly, the author expressed his concerns about the methodology used; "...it must be recognized that the difficulties in accurately replicating observations may well result in overestimation of the environmental influences on these characters. Valid transmissibility estimates must await the development of more refined observational technique" (Nichol, 1989; p. 57).

From both forensic and anthropological views, whether the traits are polygenic or the result of a single gene, heritability is the main focus. Characterization of people based on dental traits and size is actually inferring their genetic make-up or genotype. This is also the fundamental basis for my research project. The sample selected represents third or fourth generation Malaysians from three major geographic areas: India, China and South East Asia. This provides an opportunity to observe dental variation or the phenotype variation within each ethnic group and between ethnic groups using dental traits since their liability has been shown to be strongly controlled by genetics. Considering the environmental influence on the tooth

morphology and size, only significantly deviant phenotypes caused by environment will be excluded from the study.

2.5 Sexual dimorphism in the human dentition

2.5.1 Role of sex chromosomes and hormones

Many studies of human odontometrics have shown that teeth of males are generally larger than those of females (Garn *et al.*, 1964; Garn *et al.*, 1967; Lunt, 1967; Hanihara, 1978; Kieser *et al.*, 1985; Yuen *et al.*, 1997), with the noted exception of a few South American tribes e.g. the Ticuna (Harris and Nweeia, 1980a). From these studies it can be observed that the pattern and magnitude of sexual dimorphism varies between populations, suggesting a potential genetic influence (Garn *et al.*, 1967). Additional support for a genetic influence, mediated through the sex chromosomes, has been provided by family (sibling) correlation studies (Garn *et al.*, 1965b; Garn *et al.*, 1967), from individuals with sex chromosome anomalies (Alvesalo *et al.*, 1977; Alvesalo and Chapelle, 1981; Alvesalo and Tammisalo, 1981; Alvesalo *et al.*, 1987; Alvesalo *et al.*, 1991) and molecular studies (Lau *et al.*, 1989; Nakahori *et al.*, 1991). Direct and indirect evidence of sexual dimorphism in the human dentition, additional to sex chromosome effects, can be derived from studies of the role of androgens (Garn *et al.*, 1965a; Garn *et al.*, 1965d; Dempsey *et al.*, 1999; Schwartz and Dean, 2005).

Garn *et al.* (1965b) reported that sibling correlations support X-chromosomal involvement in determination of tooth size. Analyses revealed higher sister-sister correlations, varying from 0.46-0.82 with an average of 0.64, compared with brother-brother correlations (average of 0.38) and brother-sister correlations (average of 0.21). Additional information concerning a genetic control of the sexual dimorphism in tooth size came later, when Garn *et al.* (1967) found significant correlations for most of the comparisons of brother-sister differences within the same family, however, the results did not identify whether autosomal genes or sex chromosomes were involved.

Studies using individuals with chromosomal aneuploidies (a loss or duplication of chromosomes) provide opportunities to elucidate the role of both sex chromosomes in determining development of tooth crown structures, including dentine and enamel. Such types of studies require comparisons with a control subject who is a non-affected relative and also with normal populations. For example, using super-males with the chromosomal constitution 47, XYY, enables researchers to test the specific role of extra Y-chromosome on the development of tooth crown structures.

The majority of research conducted on the teeth of 47, XYY males has used radiographs to quantify the amount of dentine and enamel, thus enabling elucidation of the specific effects of sex chromosomes on dentine and/or enamel. Other studies have used mesiodistal and buccolingual measurements to quantify the cumulative effects on tooth crown size.

Studies of humans with sex chromosomal anomalies were pioneered by Alvesalo and colleagues. Reviews of the role of sex chromosomes are presented first for Y-chromosome and then for the X-chromosome. Alvesalo *et al.* (1977) studied a small sample of eight 47, XYY males and found that their mesiodistal and buccolingual tooth diameters was larger than normal control samples, except for two variables involving the canine tooth. They hypothesized that the extra Y-chromosome exerted direct growth promoting effects by inhibiting cell differentiation, so that internal dental epithelium had a longer time for cell mitosis (proliferation) that led to increased tooth size. However, this method could not reveal which tissue contributed to the larger tooth crown size, and the presence of an extra Y-chromosome appeared to have little effect on the canine tooth dimensions. Another study by Townsend and Alvesalo (1985a) used a larger sample of 47, XYY males and reached similar conclusions. They investigated the mesiodistal and buccolingual tooth crown diameters of 21 Caucasian 47, XYY males. Eighteen of 28 measurements were significantly larger than in the control group. All measurements, except the buccolingual dimension of the upper canine, were larger in the 47, XYY group.

Tooth crown tissue structures measured using standardized radiographic techniques enable calculation of the thickness of dentine and enamel. This method provides an opportunity to gain information about specific crown tissues affected by the sex chromosomes. Alvesalo and Tammisalo (1985) found that an extra Y-chromosome increased both dentine and enamel thickness in 47, XYY males. These findings supported results from previous research of Alvesalo *et al.* (1977), Alvesalo and Tammisalo (1981) and Townsend and Alvesalo (1985a) that showed a larger tooth size in the affected sample. Alvesalo *et al.* (1977), and Townsend and Alvesalo (1985a) speculated that the action of the Y-chromosome was either via the direct effect of gene(s) residing on the Y-chromosome or via the effect of heterochromatic contents on cellular activity. Earlier findings showing tooth size reduction in two males with deletions of the long arm of the Y-chromosome by Alvesalo and Chapelle (1981) suggest the possibility of direct gene(s) effect, however, as Townsend and Alvesalo (1985a) pointed out, heterochromatin content in the Y-chromosome is still sufficient to regulate cell mitosis at the late synthetic phase of the cell cycle.

The role of the X-chromosome has been studied using individuals with sex chromosomal anomalies: namely the loss or duplication of the X-chromosome. Alvesalo and Tammisalo (1981) measured the dentine and enamel thicknesses in 45, X individuals using standardized radiographs, and suggested that both X- and Y-chromosomes had roles in promoting dentine and enamel development. The X-chromosome was found to have an effect on the enamel, and less or negligible effect on dentine formation; whereas the Y-chromosome was found to affect both the dentine and enamel. Since the commencement of dentine formation occurs at an earlier stage of tooth crown development, the determination of dentine thickness is thought to be due to proliferative activity of the internal dental epithelium whereas enamel thickness is influenced by ameloblastic activity (Alvesalo and Tammisalo, 1981). Tooth crown modification in individuals with sex chromosome aneuploidies not only affects tooth size but also tooth morphology. There is evidence that tooth crown morphology undergoes simplification in 45, X individuals (Kirveskari and Alvesalo, 1982).

Townsend and Alvesalo (1985b) studied 77 47, XXY males (Klinefelter Syndrome) to elucidate the role of the X-chromosome in tooth size development. It was found that all tooth crown measurements, except those of the canine, were larger in the sample group. They also noted that buccolingual dimensions were not affected as much as mesiodistal dimensions. They explained these findings from two points of view. Firstly, since the buccal and lingual aspects of teeth have thinner enamel than the mesial and distal surfaces and the X-chromosome affects enamel deposition, any aberration in the number of X-chromosomes would logically produce more effect on the areas with a thicker enamel layer. Secondly, the mesiodistal dimension is determined earlier than the buccolingual dimension, and there is a tendency for later developing parts to undergo cell stabilization. Further evidence of the role of the X-chromosome role was revealed in a study where Alvesalo *et al.* (1987) used a standardized radiograph technique to measure the enamel thickness of super females (47, XXX individuals). They found that the enamel was thicker in super females than in control samples, which strengthens the evidence that the X-chromosome influences enamel thickness.

Additional information has been revealed about X-chromosome interaction from studies of individuals with mosaicism, e.g. 45,X/46,XX (Varrela *et al.*, 1988). Varrela and his colleagues found that X-chromosome pairs were capable of stabilizing the growth of developing teeth. There were differences between 45, X/46, XX and 45, X individuals in tooth dimensions that led the authors to suggest that the presence of a normal 46, XX cell line provided an advantage for normal cell selection in the developing tooth germ. They further showed that there was a tendency for early-developing teeth to be more affected than late-developing teeth

e.g. incisors and first molars over canines and second molars. There was gradual tooth development stabilization in later developing teeth in individuals affected with chromosomal abnormalities.

Alvesalo *et al.* (1991) measured the dentine and enamel thickness of the right central incisor and upper canine in 47, XXY males using radiographs and confirmed previous findings (Alvesalo and Tammisalo, 1981) that the Y-chromosome promoted dentine and enamel growth, while the X-chromosome influenced only enamel growth.

Townsend and Alvesalo (1995) found an altered overall crown shape associated with a reduction of enamel thickness in a large sample of 45, X (Turner's syndrome) individuals. The reduction of enamel thickness was not only observed in mesio-distal dimensions, but also in intercuspal distance. Interestingly, the buccolingual dimensions remained unaffected. Townsend and Alvesalo (1999) provided additional evidence for the role of the X-chromosome using individuals with an additional X-chromosome, 47, XXY males. As expected, they found that the extra X-chromosome not only promoted larger tooth sizes (except in the BL dimensions) but also greater intercuspal distances.

As odontogenesis occurs in pre- and early post-natal life (except for the third molar), the role of hormones has often been assumed to be unimportant, however, Dempsey *et al.* (1999) reported the influence of androgens (sex hormones) on tooth size according to gender during a tooth germ stage in a sample of twins. They found that females from pairs of opposite sex dizygotic twins have larger teeth than same sex twins and singleton females. The authors postulated that the increased size was due to an increase in cell proliferation at an early stage of tooth germ development. This increase in cell proliferation may be influenced by androgens from twin brothers. The authors also found that the trend in the magnitude of sexual dimorphism followed previous studies that showed buccolingual dimensions were generally more dimorphic than mesiodistal dimensions, and that the canine was the largest tooth. Interestingly, the results of this study suggested that the canine size was independent from hormonal influence. A preliminary study by Schwartz and Dean (2005) suggested that sex hormones may affect odontoblastic activity of the third molars using measurement of dentine area on a sectioned tooth. Other evidence of hormonal influence on dental development, although not directly on tooth size determination was provided by Garn *et al.* (1965d). Dental development, such as developmental age, was retarded in cases of hypothyroidism and hypopituitarism, while in endocrine sexual precocities, dental advancement was prominent.

In conclusion, despite small sample sizes in some of the research, it is clear that the differential roles of sex chromosomes on the dentine and enamel give rise to sexual

dimorphism in tooth size and morphology. The influence of sex chromosomes on dental development appears to occur at the very early developmental stages via internal dental epithelium mitotic activity and amelogenesis. Additional evidence, other than that from sex chromosomal aneuploidy samples, that support the role of sex chromosomes for enamel formation were from the findings by Alvesalo and Chapelle (1981), Lau *et al.* (1989), Nakahori *et al.* (1991). Gene(s) controlling amelogenin (enamel protein) formation are located on the X and Y chromosomes. From tooth size comparisons, the Y chromosome appears to demonstrate its effects on both mesiodistal and buccolingual dimensions, whereas the X-chromosome fails to illustrate any effect on BL dimensions. The effect of the X-chromosome on the enamel is apparently not just on the MD dimension but also on the frequency of occurrences of the dental traits. Sex difference mechanisms in the canine tooth still remain unclear from both hormonal and sex anomalies studies.

Little is still known about which tooth crown tissues actually contribute to sexual dimorphism. Moss (1978) postulated that the sexual dimorphism in human canine size could be due to differential activity in amelogenesis. He proposed that as canines took longer to complete crown development in males there was, therefore, more time for enamel to be laid down. In contrast, Stroud *et al.* (1994), Harris and Hicks (1998), Shields (2000), and Schwartz and Dean (2005) showed that the enamel was in fact thicker in females than males. Furthermore, Schwartz and Dean (2005) reported that sexual dimorphism could actually be due to the amount of dentine. Using wet tooth weight in heterogenous samples, they showed that the dentine from males weighed more than that from females. Another study by Harris and Hicks (1998) also provided evidence that the dentine thickness in maxillary incisors were significantly greater in males by 6.5%.

It is possible that the Y-chromosome could be influencing sexual dimorphism in the human dentition. In addition to persuasive evidence from correlation studies and sex chromosome aneuploidy samples, hormonal influences should also be taken into consideration in the variation of dental sexual dimorphism.

2.5.2 Magnitude and pattern of sexual dimorphism in human populations

Homo sapiens show a diminishing trend of sexual dimorphism when compared to primates, who can exhibit sex differences of up to 50% or more (Garn *et al.*, 1967). Frisch (1979) reviewed the effect of cultural influences on the reduction of sexual dimorphism in hominids. He opposed Wolpoff's theory (Wolpoff, 1976) that the introduction of tools and

weapons, which functioned as canine replacements, had an effect on reduction of canine size based on findings in fossil remains. He agreed, however, that cultural activity had also influenced sexual dimorphism reduction through diverse activities such as division of labour, hunting, tool making and social organization, but not tool making alone. A combination of these activities according to Frisch, would lead to larger body size in females, enabling larger offspring to be delivered, leading to reduced inter-male rivalry which ultimately would result in reduced sexual dimorphism.

Regardless of the sex selection process in the course of man's evolution, the discussion about sexual dimorphism should be extended to normal samples in diverse populations. From what we understand of the role of sex chromosomes, hormones and also the environment in determining sex predilections, it would be expected that variations would exist in the degree and magnitude of sexual dimorphism in different populations and in different tooth classes.

2.5.2.1 General pattern of sexual dimorphism in tooth size

Many researchers have shown that the teeth of males are larger than those of females, with the noted exception of Native South American, (Ticuna) dentitions. Lunt (1967) found sex differences to be pronounced in the canines of male Medieval Danes. In more recent populations, Rosenzweig (1970) measured the tooth size of six Mediterranean groups and showed that the teeth of males were larger than those of the females in all six groups in 33 of 48 pairs of comparisons. Liu (1977) found significant sexual dimorphism in mesiodistal and buccolingual tooth measurements of Taiwanese Aborigines (Ami and Atayal), however, Kaul and Prakash (1984) found that in Jat's population, teeth from males were significantly larger than teeth from females in all variables except UP1 and LI2 for mesiodistal dimension (the third molar (M3) was not measured) while in the buccolingual dimension (only post-canine teeth were measured) all variables were sexually significantly larger in males except for the lower second premolar. Macko *et al.* (1979) also found teeth from males to be significantly larger in 113 Black Americans, except the mesiodistal dimensions of upper first premolars and lower first premolars (M3 not included in the study). Moorrees *et al.* (1957) reported on the mesiodistal diameters of 184 North American children. The teeth from males were significantly larger in 13 of 14 variables with the exception of the upper lateral incisor. In studies of South African populations, the most dimorphic teeth were the upper third molar for mesiodistal dimension and the upper canine for buccolingual dimension, in both groups; San and Central Sotho (Haeussler *et al.*, 1989), however, not all tooth size variables were larger in males. The

mean of the mesiodistal dimension in the upper lateral incisor and the mesiodistal dimension in the upper second premolar were larger in the females for both groups (Haeussler *et al.*, 1989). Rare but interesting findings were reported by Harris and Nweeia (1980a), who found lack of tooth size differences between males and females in South American natives, the Ticuna Indians. Sexual dimorphism percentages (differences between mean male and female measurements divided by mean female measurements) were around zero with the average for 14 mesiodistal diameters being 0.45% and 1.73% for 14 buccolingual diameters.

2.5.2.2 Magnitude and pattern of sexual dimorphism in tooth crown dimensions

Several studies have shown that the magnitude and pattern of sexual dimorphism varies between populations and between tooth classes. The apparent variability could be masked by sampling variation, differences in methodology or could be a true variation in different populations (population variations).

Garn *et al.* (1967) found the pattern (ranking) of sexual dimorphism in tooth size (mesiodistal) in a white population from Ohio to be canine (largest difference) to incisors (the least dimorphic). The sexual dimorphism exhibited in the mesiodistal dimension of the lower canine was 6.4% (ranked first) and of the incisor was 1.3% (Garn *et al.*, 1967). Even though the largest sexual dimorphism was seen in the mesiodistal dimension of lower canine, this was not replicated in the buccolingual measurements. In fact the pattern was reversed, with the buccolingual measurements for the canine ranked 14th which was the least dimorphic. This suggests that the degree of sexual dimorphism in mesiodistal dimensions is independent of buccolingual dimensions. The largest absolute mean mesiodistal difference between males and females in the Ohio cohort was recorded on the lower first and second molars, 0.52mm and 0.45mm respectively, and on the mandibular and maxillary canines, 0.44mm and 0.42mm respectively. When the authors applied the same calculations to nine alternate populations, the magnitude of the canine sexual dimorphism varied between 4.1%-7.3%. From these results they concluded that the patterning and magnitude of sexual dimorphism in tooth size varies from group to group.

Several researchers have reported some variation in sexual dimorphism in the canine tooth for different populations. Most evidence confirms that the canine tooth exhibits the greatest amount of sexual dimorphism (both maxillary and mandibular teeth), although in a few populations the strongest dimorphism is exhibited by other teeth, for example the lateral incisor and premolar teeth. Pettenati-Soubayroux *et al.* (2002) showed the upper canine attained the highest dimorphism for mesiodistal measurements in 18th century skeletal remains from

Marseilles. They reported dimorphism for several teeth as follows: upper canine 10.3%, upper lateral incisor 7.2%, lower canine 4.6%, upper central incisor 1.6% and lower lateral incisor 0.2%. Lund and Mornstad (1999) reported percentages for sexual dimorphism for mesiodistal diameters in a Swedish population as 8.5% for the upper canine, and 9.6% for lower canines which was higher than previously reported in the Ohio population (Garn *et al.*, 1967). Moorrees (1957) reported on sex difference trends in Aleut individuals. Sex differences in the lower canine were larger than in the upper canine mesiodistally, however there was no significant difference in the magnitude of the sexual dimorphism between upper and lower canines in buccolingual dimensions. Brown and Townsend (1979) provided similar findings on sexual dimorphism patterns and magnitude, reporting that the most dimorphic teeth in Australian Aborigines were the upper canine and the lower canine. Generally, buccolingual dimensions were more dimorphic than mesiodistal dimensions with averages of 4% and 3% respectively. Noss *et al.* (1983a) found in a sample of 1177 Pima Indians, the greatest sexual dimorphism to be the mesiodistal dimension of lower canines (5.3%), and the buccolingual dimension of lower canines (3.6%).

Sexual dimorphism inter-relationships with tooth classes reveals evidence that sexual dimorphism and tooth size are not independent. Garn *et al.* (1967) proposed the canine dimorphism theory, which states if the canine has the greatest dimorphism then the adjacent teeth, the lateral incisor and first premolar would also have greater dimorphism than other tooth classes. They based their theory on the study of sexual dimorphism in eight primate species and genera, and intra-familial brother-sister correlations of tooth size differences of central incisor-canine (I1-C), lateral incisor-canine (I2-C), first premolar-canine (P1-C), second premolar-canine (P2-C); where the lateral incisor and first premolar showed higher dimorphism correlations. In addition, they also found that sexual dimorphism within the same morphological class showed greater correlations. Kieser *et al.* (1985), using percentages of sexual dimorphism, reported that their results did not support the canine field theory, where the mesiodistal UC ranked first, mesiodistal LC second and mesiodistal LI2 ranked last.

The pattern and magnitude of sexual dimorphism using several different samples has also been studied. The hypothesis for this research design was that any apparent variability in the pattern and magnitude of sexual dimorphism should come from the population and possible sampling differences, since the methods used by the same operators were specific and standardized. Kieser and Groeneveld (1989) presented percentages of sexual dimorphism for maxillary mesiodistal and buccolingual dimensions in three populations; 100 male and 102 female Lengua Indians, 59 male and 66 female Caucasoids, and 106 male and 100 female

Negroes. Common sexual dimorphism patterns could be observed: the buccolingual dimension exceeded the mesiodistal dimension only in two teeth the lower first premolar (LP1) and lower second premolar (LP2), and none of the average sexual dimorphism in buccolingual dimensions exceeded the mesiodistal dimensions. The range of sexual dimorphism for the mesiodistal diameter in Lengua Indians was 0.7%-7.5%, in Negroes 1.7%-8.9% and in Caucasoids 3.5%-8.8%. The most dimorphic tooth dimension was the mesiodistal of the canine in Lengua and Caucasoid groups, whereas in Negroes the upper lateral incisor (UI2) was the most dimorphic. For the buccolingual dimension the canine tooth displayed the strongest dimorphism only in Lengua Indians. For Negro and Caucasoid populations the strongest dimorphism resided in UI2 and the upper second premolar, respectively.

Hanihara (1978) studied differences in sexual dimorphism in five populations using mesiodistal dimensions from eight teeth: upper central incisor (UI1), upper canine (UC), upper second premolar (UP2), upper second molar (UM2) and lower lateral incisor (LI2), LP1, lower first molar (LM1) and lower second molar (LM2). He found that magnitude and patterns of sexual dimorphism were independent from tooth size. Population with larger tooth sizes, like Australian Aborigines, do not necessarily have large sex differences, in fact Japanese and Pima Indians have larger sex differences than Australian Aborigines. Furthermore, from this study the author was able to provide evidence that population variation exists for the magnitude and pattern of sexual dimorphism, at least between the five populations in his study. He used several multivariate analyses; D^2 Mahalanobis distance analyses, canonical variates and factor analyses, and all showed consistent results.

Yamada and Sakai (1992) used mesiodistal (MD) and buccolingual (BL) diameters to study sexual dimorphism variations in six population groups of Cook Islanders, which were geographically divided into two, the Northern and Southern groups. The Southern group exhibited larger sex differences than the Northern group, however, the Northern group was characterized by larger MD diameters. The degree of sexual dimorphism for the mesiodistal diameter ranged from 2.4% in the Southern islands to 4.1% in Rarotonga. The degree of sexual dimorphism in the buccolingual dimension was larger than in the mesiodistal diameter in six Cook Islanders' populations (average sex dimorphism 3.2% in MD and 5.1% in BL). From multivariate analyses (Penrose distance analyses), MD dimensions did not relate to the degree of sex dimorphism. Haeussler *et al.* (1989) supported the view that the extent of sexual dimorphism was not associated with tooth size. In research on South African populations, San who were considered microdontic, exhibited larger sexual dimorphism than the Central Sotho group, who were mesodontic (Haeussler *et al.*, 1989; Table 3, page 120). The effect of an

association between tooth size and morphology on the extent of sexual dimorphism was clearly demonstrated when Noss *et al.* (1983a) found that the Carabelli trait has almost lost its dimorphism, and the degree of dimorphism has also diminished in canine distal accessory ridge in Pima Indians, from 75.9% to 46.8% while tooth size has held constant. They suggested that morphological traits uninfluenced by tooth size, rarely showed sex dimorphism in their frequencies of occurrence.

More information on the effect of inter-correlations between variables and these effects on the pattern and magnitude of sexual dimorphism are available through multivariate statistical analyses. Potter *et al.* (1981) compared the extent of sex differences using univariate and multivariate discriminant function analyses. Sex differences in 39 of 56 variables were significant according to univariate analysis. However, from multivariate analysis only four variables appear to significantly contribute to sex discrimination and one of the four variables selected, BL LP2 dimension, was not even significant in univariate testing. Diverging results were apparent between the multivariate and univariate analyses, and the distance between males and females was exaggerated in the univariate analysis. This phenomenon was explained by Potter *et al.* as "...univariate sex dimorphism is largely dependent upon tooth size interrelationships within individuals, so that such dimorphism becomes obscured when the teeth are jointly analysed in the multivariate approach" (Potter *et al.*, 1981). They further suggested the use of both univariate and multivariate analyses as a routine measure in sexual dimorphism studies. Kieser *et al.* (1985) analysed mesiodistal and buccolingual dimensions of 125 South African Caucasoids attending an orthodontic clinic. They performed univariate and multivariate analyses to assess sex dimorphism in this population. Contrasting results were also found between univariate t-tests and multivariate discriminant function analyses. Consistent with the results described by Potter *et al.* (1981) not all significant variables in two-sample t-tests contributed to sexual dimorphism when analysed with discriminant function. The strongest coefficient of determination (R^2) contributing to sex differences was 31.5% in the mesiodistal UC and the mesiodistal lower canine fell second with 29.8%. Only eight (including two canines variables) from 22 variables which were significant for sex difference using univariate analysis were selected as best sex discriminators with multivariate analysis. The other six variables selected were MD UM2, BL UP1, MD UI1, BL LP1, BL LP2, MD LI1.

2.5.2.3 Magnitude and pattern of sexual dimorphism from the frequencies of tooth morphology (non-metric crown traits)

The patterns and magnitude of sexual dimorphism for tooth crown morphology also vary between populations. However, in contrast to the patterns and magnitude of sexual dimorphism in tooth size analyses, most studies of morphological features do not provide supporting evidence of sexual dimorphism.

Negative findings have been reported by several authors. Garn *et al.* (1966b) found no sexual dimorphism in the frequency of occurrence of Carabelli trait in a white Ohio population. Thomas *et al.*, (1986) found no significant male-female differences in the frequency of occurrence of Carabelli trait in five Southern African populations: Negroids, Caucasoids, Coloureds (Peninsula and Namaqualand) and Indians. The sample size was 100 for each group, except the Indian group which was 92, and male-female numbers were approximately equal. Rusmah (1992) studied 320 young Malaysian dentitions and reported no sex difference in five ranked scales and present-absent dichotomized data for Carabelli trait occurrence, however, from the table of results, there is a significant association between the occurrence of Carabelli trait and sex at 1% significance level with males showing higher Carabelli occurrences. The study did not specify ethnic groups of the participants which may bias the results. Hassanali (1982) found no sex differences in the occurrence of Carabelli in Kenyans and Asians. The author used two methods of observation: direct clinical examination on 1247 Africans and 763 Asians, and observation on the models of another 298 Africans. Results showed that Carabelli incidence from direct clinical examination was lower than the incidence observed on casts. Overall, the Carabelli incidence in Africans in this study was considered high, at 68%. Kannappan and Swaminathan (1998) found no sexual dimorphism in the occurrence of Carabelli trait in a sample 648 Indians. The prevalence was 53% in the pooled sex sample. Kieser (1984) also found no sexual dimorphism in the occurrence of Carabelli trait in 240 South African Caucasoids attending an orthodontic clinic at Witwatersrand Dental School. Hershey (1979) studied Carabelli's structure on 285 Wainwright Eskimo individuals and found no sexual dimorphism evident in the frequencies of occurrence. Scott (1980) studied Carabelli trait in five major group populations; Solomon Islanders, Asiatic Indians, Southwest Indians, Bantu and South African White and reported none of the groups showed significant sex differences.

Haeussler *et al.* (1989) compared two Southern African populations, San and Central Sotho, and found no sex differences in the frequencies of occurrence of dichotomized present-

absent classifications of shovelling, double-shovelling, winging, Bushman canine, hypocone, cusp 5 (metaconule), cusp 7, distal trigonid crest, deflecting wrinkle, cusp number on LM1 and LM2, Carabelli cusp and Y-groove pattern. Hanihara (1977) found no sex differences in the frequencies of six crown morphologies in six populations: Ainu, Japanese, Australian Aborigines, Pima Indian, Eskimo and Caucasian. The author used absent-present dichotomous data on shovelling in the upper central incisor (depth of lingual fossa >0.51mm); sixth cusp, seventh cusp, deflecting wrinkle, protostylid (pit did not count as present) in the lower first molar, and cusp of Carabelli in the upper first molar (only cusp type counted as present). Turner and Hanihara (1977) reported no significant sexual dimorphism in the occurrence of 18 dental crown morphologies in Ainu populations. The traits studied were winging, shovelling, double shovel, tuberculum dentale, incisor interruption groove, canine distal accessory ridge, premolar cusp number, cusp 5, Carabelli trait, hypocone, lower incisor shovelling, premolar lingual cusp, molar groove pattern, molar cusp number, protostylid, cusp 6, cusp 7, and deflecting wrinkle. Manabe *et al.* (1992) found no sexual dimorphism in dental morphology of 150 Ami tribes from Taiwan. The morphological traits studied were shovel, double shovel, tuberculum dentale, canine mesial ridge, canine distal accessory ridge, lower second premolar lingual cusp variation, odontoma, hypocone, protostylid, cusp 5, Carabelli trait, deflecting wrinkle, distal trigonid crest, cusp 6, cusp 7, groove pattern and cusp number of LM2. Mayhall *et al.* (1982) reported no significant sex differences in the occurrence of shovelling, lower premolar groove pattern and lingual cusp number, Carabelli trait, and hypocone development in North American Whites. Turner and Scott (1977) found no sexual dimorphism in the occurrence of 14 dental crown traits of an Easter Island population. The dental traits studied were shovel, medial lingual ridges, maxillary incisor marginal interruption, supernumerary cusp 5 and cusp 6 of maxillary molars, hypocone, Carabelli trait, occlusal traits on the LP1 and LP2, LM groove pattern and LM cusp number. Bang and Hasund (1972) found no sex differences in the frequency of occurrences of Carabelli structure of 99 Alaskan Eskimoes and in shovel trait occurrence of 110 Alaskan Eskimoes (Bang and Hasund, 1971). Townsend *et al.* (1990) reported no sex differences in the frequencies of occurrence and the degree of expression of entoconulid in 399 Australian Aboriginals. Earlier research had also found no strong evidence of sexual dimorphism in the occurrence of metaconule in Australian Aborigines (Townsend *et al.*, 1986).

Some other researchers have found reverse, but inconsistent, patterns of sexual dimorphism. This means that greater frequencies may occur in either sex for different dental crown traits. Iwai-Liao *et al.* (1996) found significant sexual dimorphism of Carabelli trait in two

Asian groups, 240 Japanese and 160 Chinese (Han natives) with preponderance in males. Another study in Southern Chinese populations by Hsu *et al.* (1999) reported a similar finding with significant sexual dimorphism in Carabelli trait with more expression in males. Rothhammer *et al.* (1968) studied the occurrences of winging and shovel shape in a Chilean population (73 Pewenche Indians). They reported no sexual dimorphism in winging, but significant differences in shovel shape was apparent. Townsend and Brown (1981a) found a greater expression and occurrence of Carabelli trait in male Australian Aborigines. Escobar *et al.* (1977) found significant sex differences in shovel, Carabelli trait, peg shape (more in male) but no significant differences in protostylid, or winging in a group of 540 Quekchi Indians from Guatemala. Another study using a large Melanesian sample was conducted by Harris and Bailit (1980), and found the occurrence and expression of metaconule in 1217 living Melanesians to be more significant in females. Scott (1977b) studied the frequency and degree of expression of upper and lower canine distal accessory ridge in seven Southwestern Indian and two American White groups. The results reported that males show consistently higher total frequencies and more pronounced trait expressions.

The literature reveals strong support for the view that sexual dimorphism is small in the majority of dental crown traits in many populations. As there was no clear trend in the magnitude and pattern of sexual dimorphism evident from previous research, research on a Malaysian sample to elucidate any sex differences in metric and non-metric traits was deemed necessary, and appropriate. Despite a study by Rusmah (1992) on Carabelli trait, further studies on other metric and non-metric traits involving the several ethnic groups who reside in Malaysia may enable comparison and clarification of several questions including inter-population variation of the magnitude and the pattern of sexual dimorphism for tooth size and morphology; variable inter-correlation effects on the canine field and the effect of different statistical analyses on the interpretation of sexual dimorphism in this population.

2.5.2.4 Sex prediction models

Even though the degree of sexual dimorphism in modern humans is not as large as in primates, several scientists have tried to explore its application in forensic dentistry and archaeology. Since the dentition is frequently well preserved in fossils and the majority of forensic victims, any retained information may be useful in sex prediction. This alternative identification method could have a role when sex prediction using genetic material has failed due to contamination, protein degradation or insufficient material for analysis. Another possible application could be in young adolescent victims where post-cranial methods would not be

applicable. Tooth size and shape are determined early in life, meaning their sex difference potentials are also determined early.

Many forensic and archaeologic researchers favour the use of discriminant function analyses to assess separation between males and females using dental variables, and stepwise analysis to select the best discriminators. Linear discriminant function formula can be used to assess the hit-ratio or success rate of the formula. Considering the potential for loss of teeth in fossil or human remains, the less teeth required in the linear discriminant function to obtain a high hit ratio would be the most beneficial.

Garn *et al.* (1977) used discriminant function analysis to estimate sexing performance in 109 boys and 95 girls, all Caucasian. They used several measurements; mesiodistal, buccolingual, mesiodistal/buccolingual ratio (tooth shape) and found the best combination using three measurements mesiodistal, buccolingual and tooth shape. They found that mesiodistal dimensions better discriminated than buccolingual measurements and both simple mesiodistal and buccolingual measures performed better than tooth shape. Using mesiodistal dimensions of 14 teeth, (except M3), up to 86% correct sexing was achieved. Correct sexing improved to 87% using the best possible combination of discriminators. Using mesiodistal measurements alone, and as few as six teeth; upper canine, lower canine, lower second molar, upper lateral incisor, lower lateral incisor and upper second premolar, 85% correct sexing was achieved (maximum discriminatory effectiveness for mesiodistal measurements). This outcome supports the potential use in forensic and archaeological investigations. Despite convincing results, the authors did not provide details of the best possible combinations or discriminant variates. The results could be exaggerated, and may not have been tested for generalization, since the measurements obtained and sex assignment tests were from the same individuals.

Garn *et al.* (1979a) used combinations of root lengths (measured from radiographs) and crown size (mesiodistal and buccolingual) of mandibular teeth in 16-17 year old participants in a longitudinal study at the University of Michigan. Single root measurements performed better than a single measurement using mesiodistal or buccolingual dimensions. Combinations of crown measurements and root length for each single tooth (canine to second molar) did not improve discriminatory effectiveness. Using stepwise discriminant function analysis they added 13 measurements that provided maximum discriminatory effectiveness at 84%. The 13 measurements comprised four root lengths, five mesiodistal crown diameters and four buccolingual dimensions. The second best result used a total of six measurements from the canine and second molar; two root lengths, two mesiodistal diameters and two buccolingual

dimensions, generating 82% correct sexing. The results improved to 87% with the addition of lower incisors, I1 and I2. The best combination of teeth and dimensions were the following:

Root length: C P1 P2 M1 M2

Mesiodistal crown diameter: I2 C P1 M1 M2

Buccolingual crown diameter: C P2 M2

Iscan and Kedici (2003) utilized discriminant function analysis on 100 young adult Turkish students, recording buccolingual measurements on 14 teeth. Multivariate analyses indicated that UC, LC, and LM2 contributed the most to the functions. The best total average success rate was 77% using the first function comprising UC, LC and LM2 (all variables) and the second function comprising UC (all maxillary variables). The results using cross-validated predicted group memberships were not significantly different from the original. Discriminant analysis performed better in females than males.

Ditch and Rose (1972) attempted sexing on skeletal remains of North American Indians using multivariate discriminant analysis on MD and BL tooth measurements. The results were very convincing with correct classification in the base samples of 88.7%-95.5%. Sex prediction using discriminant formulas from the base sample were applied on 46 test samples to assess whether the formula could be generalized for that population. The success rate ranged from 80%-100% in six linear discriminant formulas (average correct classification 93%). The variables selected in the formulas were BL UC, MD UC, BL UI1 for the first formula (88.4%); BL LC, BL LI1, MD LI1 for the second formula (90.7%); BL LC, BL UC, MD UC, BL UI1 for the third formula (90.7%); BL UC, MD UP2, BL UM1, BL UP2, MD UC for the forth formula (91.0%); BL LC, MD LP1, BL LP1, MD LM1, BL LP2 for the fifth formula (88.7%); and BL LC, BL UP2, BL UM1, MD UC, BL UC for the sixth formula (95.5%). Care should be exercised in interpretation of the test sample as the samples were not equally divided, leading to the possibility that some bias could occur. In addition, the male sample size was very small. Another potential confounding factor was the fact that the actual sex of the sample was uncertain and unconfirmable, with comparison concordances being done against post-cranial sex determination by two other independent researchers using the long bones and pelvis.

Brown and Townsend (1979) utilized discriminant function analysis of dental dimensions in 133 male and 126 female Australian Aborigines. The correct assignment of sex varied, using single tooth measurement in 259 total samples, from 53% for the LM2 mesiodistal diameter to 71% for the buccolingual diameter of UC and mesiodistal diameter of LC. Sex estimation slightly improved using combined mesiodistal and buccolingual diameters on single teeth. The range of correct sex estimation was 56% for the UP1 to 74% for the LC. The maxillary canine fell second

best with 71% then the molars: UM2, LM2 with 66%, and UM1, LM1 with 65%. Additional analyses using 21 different combinations of tooth size provided better success rates, which generated 9 functions with not less than 75% correct classification tested in the basic sample. The highest achievement of 85% came from Function 1 which included all completed maxillary, mandibular, MD and BL dimensions. There was a trend of reduction in the correct classification rate using the test sample. The best discrimination came from Function 2 (mesiodistal dimension on all maxillary and mandibular teeth except the third molar) which was fifth best using the basic sample, with 76% correct classification. From a practical forensic view, Functions 6 and 8 seemed reasonable with success rates of 79% and 73% using the basic sample, and 73% and 71% using the test sample. From these results, the authors concluded that the canine dimensions were the most efficient discriminators.

Sciulli *et al.* (1977) used only canine teeth to determine sex in a prehistoric Ohio Valley Amerindians skeletal group (57 females and 52 males). Linear discriminant function generated 20.6% misclassification that was as successful as sexing using postcranial bones, however, once again, the true sex was unknown. Sex was determined against the estimated sexes using the skull and pelvis morphology prior to teeth measurements. The linear discriminant function comprised the breadth (buccolingual dimension) of the upper and lower canines.

Haeussler *et al.* (1989) reported sex classification rates for San and Central Sotho of 84% and 71%, respectively using discriminant function analyses, however, the variables exhibiting the best discriminators were not disclosed. Using the same statistical method, Potter *et al.* (1981) reported a 79% success rate using four best discriminators in the Filipino dentition and Kieser *et al.* (1985) achieved a high success rate of 71%-93%, in a South African population utilizing eight variables.

Pettenati-Soubayroux *et al.* (2002) used the relative risk proportion of four dental indices to assess the success rate in sexing skeletal remains from the 18th century. The dental indices were the difference in the maxillary I1 and I2 mesiodistal diameters, the difference between the maxillary incisor and the canine, the ratio of upper lateral incisor over central incisor mesiodistal diameters and the difference between lower canine and upper lateral incisor mesiodistal diameters. The performance using these indices were not as good as previous reports on other populations analysed with discriminant function analysis. The best achievement was 58% correct sexing using the lower dental index, being the difference between the lower canine and upper lateral incisor. In addition to low performance, the reliability for each measurement was not reported.

Lund and Mornstad (1999) studied 58 dental casts belonged to 29 males and 29 females from a Swedish population. They only provided average differences between male and female tooth size. From univariate Student's t-test, 27 of 56 dimensions were significant at $p<0.05$ however, their results can only be considered preliminary without any attempt to evaluate the error rate and validity in estimating sex using multivariate analyses. Their conclusion that the canine dimorphism from the univariate analysis supports its usefulness in gender (sex) determination for a Swedish population was too simplistic.

Rao *et al.* (1989) found an alternate way of estimating sex. Using 766 students from South India (382 males and 384 females) they tested a formula that took into account maximum canine mesiodistal diameter and inter-canine arch width (left canine tip to right canine tip). They called the formula the mandibular canine index (MCI). The MCI was calculated as follows:

$$\text{MCI}=\frac{\text{Mesiodistal crown width of mandibular canine}}{\text{Mandibular canine arch width}}$$

For the purpose of sex assignment, the value of MCI needs to be compared against a standard MCI value. The standard MCI formula was as follows:

$$\text{Standard MCI}=\frac{(\text{Mean male MCI}-\text{SD})+(\text{Mean female MCI}+\text{SD})}{2}$$

For this sample they found that the standard MCI value was 0.274. The MCI derived from the dental casts were then compared against this value. An MCI value larger than 0.274 was assigned as male, and a MCI value equal or less than 0.274 was assigned as female. The success rates using this method in this sample were 84.3% for males and 87.5% for females, which was comparable to the results of Ditch and Rose (1972) and Garn *et al.* (1977). Even though this method offers an alternate way of sexing, it was based on the lower anterior dentition which could be prone to trauma and wear.

In this PhD project, the main purpose is to explore and utilize all possible variables especially posterior teeth using MD and BL dimensions, as posterior teeth survive trauma and other extreme conditions better than anterior teeth. Rao's method, however, will be tested on this sample in a future project.

From the published literature the success rate using tooth size in many populations offers potential for this discriminant method to be used in Malaysian samples. However, as Kieser and Groeneveld (1989) pointed out, there are some problems with low correct allocation rates despite a high hit ratio using linear discriminant variates. As a precaution, test samples that are not involved in generating the linear discriminant variates should be employed to assess linear discriminant variates generalizability for that population. In addition, morphological dental traits will be considered to assess applicability to sexing the Malaysian samples. This will be

dependent on how the sex dimorphism in morphological traits varies in this sample and whether multivariate analysis will be able to detect sex differences, and provide sex prediction models.

2.6 Bilateral asymmetry in the dentition

Many paired structures in humans, e.g., hands, ears and teeth appear to be symmetrical even though this symmetry is usually not exact. Van Valen (1962) defined asymmetry as fluctuating, directional and antisymmetry. Fluctuating asymmetry is a condition where subtle differences occurred at random between paired structures due to the organism's inability to buffer developmental stress or 'noise'. In contrast, directional asymmetry is expressed as consistent differences between antimeric structures due to systematically greater development on one side than the other.

Irrespective of the use of metric or non-metric data, directional asymmetry is not evidenced statistically in the research (Kieser *et al.*, 1986; Kieser and Groeneveld, 1988) although Townsend and Brown (1980) have reported some evidence indicating directional asymmetry in several tooth dimensions. Even in some situations where the differences reached a significant level, the magnitude of the difference was not large enough to conclude that the difference was actually biologically meaningful. Potter *et al.* (1976) showed that common genetic factors acted on both the right and left sides of the dentition. This genetic analysis supports the method for scoring and measuring teeth that uses data obtained from a tooth on one side and when the data cannot be obtained e.g. due to caries or restorations, replacement with the antimere is acceptable (Harris and Bailit, 1980; Skrinjaric *et al.*, 1985). In order to gain a clearer picture of within-group variations, Harris and Bailit (1980) suggested that it was preferable to observe both sides to provide more accurate frequencies of occurrence and to gain a clearer picture of within-group variations. Another option is to observe both sides but record the strongest phenotype expression for that individual (Scott, 1977b; Skrinjaric *et al.*, 1985). This approach has been applied to non-metric data that appear to follow a quasi-continuous distribution.

Several researchers have reported a high concordance rate for bilateral symmetry of non-metric dental traits and a significant association between left and right teeth for metric features. Garn *et al.* (1966c) concluded that cusp number and grove pattern were suitable for genetic analyses except that caution was needed when traits on the second molar were used, as asymmetries occurred more frequently than on the first molar. The concordance rate in the first molar was more than 95% for cusp number and 97% for groove pattern, while in the second molar the concordance rate for cusp number was 97% and for groove pattern was

80%. Baume and Crawford (1979) assessed bilateralism of dental traits in four Mexican Indian groups and two Afro-Belizean dentitions using Kendall rank '*tau*' coefficient. Non significant differences were noted between groups with '*tau*' values being: shovelling 0.88-0.99, Carabelli trait 0.79-0.93 and protostylid 0.70-0.85. Metaconule expression has also been found to occur symmetrically in Melanesian samples (Harris and Bailit, 1980). The percentages of symmetry were 84.0% with a correlation coefficient r=0.74 on UM1; 76.0% on UM2 with r=0.55 and 71.0% on UM3 with r=0.57. Noss *et al.* (1983b) reported generally low percentages of asymmetry in Pima Indians as follows: Carabelli trait on the upper first molar (♂, male; ♀, female) (♂17.7%, ♀15.4%), hypocone on the upper second molar (♂16.8%, ♀21.9%), metaconule on the upper first molar (♂8.1%, ♀12.3%), entoconulid on the lower first molar (♂15.1%, ♀17.4%), metaconulid on the lower first molar (♂16.0%, ♀14.6%), protostylid on the lower first molar (♂17.3%, ♀19.5%). In addition, the Kendall rank '*tau*' added evidence to support bilateralism as follows: Carabelli ♂0.85, ♀0.85; hypocone ♂0.81, ♀0.80; metaconule ♂0.82, ♀0.75; entoconulid ♂0.85, ♀0.77; metaconulid ♂0.73, ♀0.73 and protostylid ♂0.83, ♀0.80. Townsend *et al.* (1990) found significant association of entoconulid frequencies and expression on corresponding right and left teeth in Australian Aborigines. Percentages of asymmetry excluding absence-absence pairs were as follows: 14.4% on LM2, 11.3% on LM1 and 6.9% on LM3. There appears to be a pattern consistent with the frequency of occurrence of the traits 50% on LM2, 70% on LM1 and 80% on LM3, low frequency of occurrences tend to have a relatively higher asymmetry. This could be due to bias from high occurrences of absent-absent pair in low frequencies traits.

In contrast, Meredith and Hixon (1954) found high levels of asymmetry of Carabelli trait in 100 European descendents. Applying 4-grade classifications the frequencies of asymmetry were: 44% of individuals showed asymmetry in total difference, 38% in discrepancy of one grade, and six percent in any two or more grade discrepancies. When size discrepancies were included, the asymmetry increased to 70% of cases. The authors did not find any significant asymmetry in the expression of Carabelli trait on the left and right sides using presence-absence classification. This finding indicates some information is lost when adopting a dichotomous presence-absence classification. Mayhall and Saunders (1986) reported percentages of asymmetry in Eskimo populations vary depending on the trait being studied. Morphological traits on the anterior teeth, like shovelling, have low levels of asymmetry (8.6%), (8.7% when absence-absence pairs are removed), however, Carabelli trait (44.3%), (49.7% when absence-absence pair removed); protostylid (35.2%), (65.2% when absence-absence pair removed); entoconulid (42.6%), (51.7% when absence-absence pair removed) and

metaconulid (26.9%), (28.2% when absence-absence pair removed) have a remarkably high asymmetry. Another striking finding was that when absence-absence pairs were removed from the calculation, the level of asymmetry tended to increase. In another study, Moskona *et al.* (1996) using a large sample from south Sinai Bedouin (>95 pairs of antimeric comparisons) reported significant bilateral asymmetry in the majority of dental traits studied. However, the percentages of asymmetry were quite low e.g. shovel (9.7%), Carabelli (22%), entoconulid (2%) and metaconulid (4.4%). In summary, the extent of asymmetry reported varies from population to population, and is influenced by the methodology used for scoring and measurements, and by different examiners.

For the purpose of assessing within-group and between-group variation, scoring and measurement will be undertaken in the study sample on both sides of the dentition. This will provide a discrimination point for deciding appropriate methodology for comparing population relationships. If the asymmetries are not biologically significant then individual counts for morphological traits and measurements from teeth on one side of the arch only will be considered appropriate.

Since tooth size and dental morphology are believed to be multifactorial polygenic traits, with environmental factors also assumed to be important in defining final tooth phenotype. Slight deviation between left and right dentition is believed to be due to the differential capability of the host to buffer environmental stress, such as disease and nutrition.

Several genetic studies suggest that fluctuating asymmetry (FA) is not determined by genetic factors but is in fact to developmental 'noise' influenced by environmental stress (Potter and Nance, 1976; Townsend and Brown, 1980). Fluctuating asymmetry has also been shown in genetically stressed samples. Suarez (1974) suggested inbreeding among Neanderthal and natural selection processes on tooth size was reflected by an elevated FA. Kobyliansky *et al.* (1992) also found that inbreeding produced an increase in fluctuating asymmetry in a group of South Sinai Bedouins. In addition to these samples, substantial large differences in FA have been found in developmentally unstable groups. Barden (1980a) and Townsend (1983) concluded that asymmetry occurred more in Down syndrome groups than in unaffected individuals. Both researchers suggested that Down syndrome individuals exhibit a lack of developmental stability to buffer environmental stress. Additional support for the stress hypothesis in congenital defects came from (Narayanan *et al.*, 1999) who compared cleft lip and palate individuals with a normal population. Similar patterns of high FA were found in this group who has been characterized as developmentally unstable similar to Down syndrome individuals.

A number of researchers have shown that the pattern of asymmetry follows morphogenetic gradients (Butler, 1939; Dahlberg, 1945; Townsend and Brown, 1981b). In this theory the mesial tooth in each morphological class is considered the most stable, displaying the least deviation from the genetic blueprint for both sides. As similar genetic influence is observed on both sides of dentition, the most stable tooth would be expected to be the least asymmetrical (Harris and Bailit, 1980; Harris and Nweeia, 1980b; Smith *et al.*, 1982; Noss *et al.*, 1983b; Townsend, 1983; Kohn and Bennett, 1986; Kieser and Groeneveld, 1988; Townsend, 1992; Moskona *et al.*, 1996). In contrast, Townsend *et al.* (1990) found no clear morphogenetic gradients in their study on the expression of entoconulid in Australian Aborigines. Several researchers have found patterns of asymmetry typical of morphogenetic gradients but with some exceptions. Mayhall and Saunders (1986) and Hershkovitz *et al.* (1993) indicated partial obedience to field theory; with the exception of mandibular incisors where the lateral incisor showed less asymmetry than the central, while Perzigian (1977) found the premolars did not follow Field Theory predictions.

Relationships between asymmetry in metric and non-metric studies would reflect the underlying susceptibility to developmental stress. Noss *et al.* (1983b), Mayhall and Saunders (1986) and Hershkovitz *et al.* (1993) found no association between tooth size and presence or absence of morphological asymmetry, and an independent relationship between asymmetry in tooth size and morphology. They proposed two hypotheses. Firstly, tooth bud formation for morphological traits and tooth size was independent, implying that the environment affected morphology and tooth size independently (Noss *et al.*, 1983b). Secondly, developmental stress influences occur at different times on morphological trait and tooth size as a result of differential timing in the development, hence resulting in independent effects on tooth size and dental traits.

In conclusion, assessment of directional or fluctuating asymmetry has implications for both biological and methodological considerations. Conflicting results could be due to true population variations, individual idiosyncratic responses to stress, differences in the methodology of quantifying asymmetry or sampling bias. Therefore, for my research project, bilateralism will be tested initially, and assessments of asymmetry and sexual dimorphism will follow to ensure that the data analyses are free from confounding factors.

2.7 Human diversity based on tooth size and morphology

Tooth size and morphology have been widely used in the assessment of population affinity and history (Hanihara, 1976; Hanihara, 1977; Turner and Hanihara, 1977; Turner, 1987; Turner, 1990; Hanihara, 1992a; Hanihara, 1992b; Shields, 1996; Hanihara, 1998; Hanihara and Ishida, 2005; Matsumura and Hudson, 2005); microevolution (Kurten, 1967; Turner, 1967; Rothhammer *et al.*, 1968; Shields and Jones, 1996); genetics (Horowitz *et al.*, 1958; Lundstrom, 1963; Blanco and Chakraborty, 1976; Lundstrom, 1977; Townsend, 1978; Townsend and Brown, 1978; Townsend, 1980; Skrinjaric *et al.*, 1985; Townsend *et al.*, 1992; Dempsey *et al.*, 1995; Pinkerton *et al.*, 1999; Hughes *et al.*, 2000; Dempsey and Townsend, 2001) and forensic applications (Tratman, 1950; Lasker and Lee, 1957; Dahlberg, 1963; Matis and Zwemer, 1971; Dahlberg, 1985; Haeussler *et al.*, 1989). In an attempt to characterize people based on their dentition, several researchers have proposed 'racial dental complexes' which consist of several morphological dental traits thought to be ethnically discriminating. It was hypothesised that groups of people who shared the same genetic background should have approximately the same frequencies and expressions of dental traits. The working tenet is that the people who have similar frequencies of occurrence of particular dental complexes would be identified as belonging to a particular race or group of people. However, racial dental complexes have been criticized by some researchers, with doubt expressed about their validity (Axelsson and Kirveskari, 1977; Mayhall, 1999). Several dental complexes will be reviewed, such as Mongoloid (Hanihara, 1967; Turner, 1987; Turner, 1990), Caucasoid (Mayhall *et al.*, 1982) and Australoid (Townsend *et al.*, 1990) and the limitations that need to be born in mind when using "dental complexes" will be highlighted. As an extension of the use of dental traits in assessing human population diversity for anthropological study, this review will discuss the possibility of expanding its application and to understand the limitation for forensic human identification purposes (Dahlberg, 1963; Dahlberg, 1985) for Malaysians. Dental traits proposed by Dahlberg (1963) as suitable for use in forensic analysis were cusp size, number and location; simple and complex occlusal cusp-groove surface patterns; individual tooth measurements; dimensional proportions between kinds of teeth (second bicuspid versus first molar); number and arrangement of teeth; root systems; occlusal and bony relationships; nature of pulp chambers and canals; microscopic tooth-surface characteristics and palatal rugae patterns. Since this project uses dental casts, only some of these could be studied.

The description from Tratman (1950) of his dental comparative study of modern Malaysian/Singaporeans (where Malays and Chinese were grouped as Mongoloids and the

Tamils as Indoeuropeans), would be the closest published material to the data in this thesis. Some of the interpretations of dental variation provided by Turner (1990) and Tratman (1950) will be discussed with a view to forensic application in Malaysia.

The first researcher to come up with the concept of a dental complex was Hanihara (1967). He proposed the Mongoloid dental complex which comprised six primary crown morphologies that occurred at high frequencies, namely shovel shape on the upper central and lateral incisors, deflecting wrinkle, protostylid, seventh cusp on the lower second molar and metaconule on the upper second molar. He believed these traits characterized Mongoloid people and suggested further exploration and application of dental complexes to the permanent teeth and other racial groups. In 1968, he proposed Mongoloid dental complexes for permanent teeth with a slight modification from the previous complex, the omission of seventh cusp distribution from the complex (Hanihara, 1968).

Turner (1987, 1990) found Mongoloid people could be subdivided into Sinodonts represented by Northern Asians and Native Americans, and Sundadonts represented by people of South East Asia. The author identified 28 dental traits on several East Asian populations including recent and prehistoric samples, namely; winging of upper central incisors (UI1), shovelling of UI1, double-shovelling UI1, interruption grooves on upper lateral incisors (UI2), tuberculum dentale UI2, mesial ridge of upper canine (UC), distal accessory ridge UC, hypocone upper second molar (UM2), cusp 5 of upper first molar (UM1), Carabelli trait of UM1, parastyle of upper third molar (UM3), enamel extension of UM1, root number of upper first premolar (UP1), root number of UM2, peg/reduced/congenital absence of UM3, lingual cusp number of lower second premolar (LP2), groove pattern of lower second molar (LM2), cusp number of lower first molar (LM1), cusp number of LM2, deflecting wrinkle of LM1, distal trigonid crest of LM1, protostylid of LM1, cusp 7 of LM1, Tome's root of LP1, root number of lower canine (LC), root number LM1, root number LM2, and odontome of upper and lower first and second premolars (U+LP 1 and 2). The author used the Mean Measure of Divergence statistic to assess the biological distance within East Asian people, and presented the derived matrix in cluster analyses for ease of interpretation. From the cladogram, Turner concluded that East Asians could be divided into the people who live in the North and the South East of East Asia. In addition to two major clusters, the South East Asian (Sundadont) division could be further divided into two minor clusters, Nepalese, Phillipinos, people from the East Malay Archipelago, Indomalaysians and Burmese in the first minor cluster, and Prehistoric Taiwanese, Thailanders, Early Mainland South East Asian, Early Malay Archipelago and recent South East Asian (people from Indochina) in the second cluster. Turner was not able to provide

a definitive explanation for these Sundadont minor clusters. He tentatively explained that the Sundadont subdivision could be due to admixture between people from the first minor cluster with neighbouring Caucasoids from India, or influence from the Arab and Indian traders, missionaries and colonists. There was also some possibility of genetic interaction from Sinodonts/northern Mongoloids. Turner postulated that the first minor cluster comprised recent populations whereas the sample in the second minor cluster comprised prehistoric populations who were more likely genetically isolated. His explanation was restricted as it did not include an Asiatic Indian sample. It is possible that inclusion of an Asiatic Indian sample and comparison with the Malays and Chinese, may have provided an explanation for the possibility of Caucasoid and Sinodont admixture in the first minor cluster.

From the 28 traits initially used to separate East Asian into North and South divisions, Turner (1990) found eight dental traits that detected significant differences in mean frequency between Sinodonts and Sundadonts. The eight dental traits were UI1 shovelling, UI1 double shovel, LM1 deflecting wrinkle, UM1 enamel extension, UM3 peg/reduced/congenital absence, LM1 three roots, LM2 four cusps and UP1 one root. All traits occurred more frequently in Sinodonts except for four-cusped LM2. Turner described the Sinodonts as having trait intensification, that is, higher frequencies of crown trait occurrences and addition for example three rooted LM1. Sundadonts have crown simplification represented by a moderate frequency of occurrences, and retention of old traits, for instance, two rooted upper first premolars (UP1).

Tratman (1950) described dental variation in pre-World War II Malaysian populations. In his paper, Tratman provided only relative anatomical descriptions of crown and root morphology between the Tamils (Indoeuropean) and Chinese/Malays (Mongoloid) except for a few dental traits where he provided some statistics. The striking points from Tratman's observations are that Mongoloids have a high frequency of shovelling, dens evaginatus of the premolars, double shovel, enamel extension (90% prevalence), taurodontism in upper and lower molars, sixth cusp on the lower first molar, short roots for all teeth generally, relatively small crowns and roots of canines and maxillary premolars, rare presentation of two separate roots for upper premolars (1st and 2nd), more complex occlusal surfaces in the molar series, larger sized lower molar crowns, less prevalence of Carabelli trait, less splayed roots of maxillary molars and extra distolingual root (10% prevalence). The above descriptions can be used as a general guide, but are definitely not sufficient to meet forensic requirements. Therefore, in my project, most of the features (observable on dental casts) described will be revisited and presented with descriptive and inferential statistics.

Mayhall *et al.* (1982) proposed a Caucasoid Dental Complex consisting of low frequencies of occurrence of shovel (males 30%, females 35%), protostylid (males 0%, females 4%), C7 (males 3%, females 6%), C6 (males 3%, females 6%), occlusal tubercles on the LP2 (males 0%, females 0%) and high frequencies of Carabelli trait (males 49%, females 34%), hypocone reduction of upper second molar (males 40%, females 48%) and bilateral counter winging (males 14%, females 15%). The frequencies of Carabelli trait only revealed differences with respect to the Mongoloid sample when cusp expressions were used. In summary, Caucasoids possess simplification patterns except for the incidence of Carabelli trait/cusp. When compared to the Sundadont characteristics, there were similarities in the general trend toward crown simplification. Even the frequencies of Carabelli trait found in this sample (Northern American White) were not that high. Matsumura and Hudson (2005) reported using the same breakpoint, and observed Carabelli frequency in Sunda Islanders was 35.8% and in Dayak 31.7%. Also worth noting is the finding of Kraus (1959) who compared Carabelli variation in three racial groups: Mongoloid, Caucasoid, Negroid. He noted that Mongoloid people possessed the highest intermediate expression (pit, furrow and tubercular) and a low frequency of cuspal type (pronounced expression) and absent (smooth surface). He concluded that Mongoloids generally display Carabelli trait more often than Caucasoids. However, the frequencies of cuspal expression did enable Kraus (1959) to differentiate Mongoloids from Caucasoids. Another study by Hershey (1979) reported similar findings to Krauss. He found high intermediate expression of Carabelli trait in Wainwright Eskimoes, who belong to Mongoloid stock, and also high overall trait presence (92%). Not only has the validity of Carabelli as a racial trait been challenged, but deflecting wrinkle and entoconulid (C6) in the Mongoloid dental complex should also be interpreted cautiously (Axelsson and Kirveskari, 1977; Axelsson and Kirveskari, 1979). They found that the frequencies of deflecting wrinkle (34.2% on LM1) and entoconulid (17% on LM1) (C6) in Icelanders, who are Caucasoids, fell in the range of Mongoloid populations.

Another dental complex has been proposed by Townsend *et al.* (1990). They found that Australian Aborigines were characterized by a high frequency of occurrence of entoconulid. The frequencies were approximately 70% on LM1, 80% on LM3 and 50% on LM2, which is the highest ever reported for a modern human population.

In my opinion, if the dental complex enables population stratification, the potential application in human identification would be by direct comparison with extreme frequencies and degrees of expressions of the dental traits in the standard dental complex, with supplemental use of multivariate analyses such as discriminant function analysis or logistic regression. The

evidence from non-metric analyses should be used in conjunction with the results from metric analysis, before decisions are confirmed.

Odontometric analyses are also useful and biologically meaningful in assessing world-wide interpopulation relationships. The results from odontometric analyses (mesiodistal and buccolingual diameters) are consistent with those based on genetic and craniometric data (Hanihara and Ishida, 2005). From 72 major populations the authors were able to characterize human populations into three main streams using mesiodistal and buccolingual diameters: microdontic, mesodontic and megadontic. Microdontic populations were made up of Native Americans, Philippine Negritos, Jomon/Ainu and Western Eurasian while Polynesian and East/Southeast Asians were mesodontic and Australian Aborigines, Melanesians, Micronesians, sub-saharan Africans were megadontic. They found that their results did not support the Mongoloid subdivision proposed by Turner (1987, 1990). The Chinese and Japanese, who are Sinodonts according to Turner, were found to be closest to the Southeast Asians, while prehistoric Jomonese were closer to Australian and Papuan populations. Contrasting results between metric and non-metric parameters have also been found in other research (Hanihara, 1976). Using metric data, Hanihara calculated phenetic distance with multivariate statistics and found that Aborigines were closer to Caucasians and American Whites than to the Mongoloid group. However, using six non-metric dental traits, mean measure of divergences statistics revealed the Aborigines were closer to Mongoloids and retained archaic dental characteristics (except Carabelli trait) as shown in Mongoloids. When considering geographical relationships, non-metric analyses seem to be more appropriate. A similar view was expressed by Lasker and Lee (1957), that non-metric traits provided better racial criteria than tooth size. In another study Sharma (1983) found consistent results between metric and non-metric data in the Tibetan dentition. Tooth size and morphological traits were comparable with Caucasoid populations, in fact, traits such as high frequency of modification of Y5 crown pattern, low frequencies of C6, C7, deflecting wrinkle and absence of protostylid clearly contrasted with the Mongoloid dental complex. In reaching this conclusion Sharma used only univariate comparisons.

Matsumura and Hudson (2005) used C-score data that represent shape components and found that the Malays, South Chinese and South Indians have a narrower MD diameter than Philippine Negritos (based on first principal components that attribute variance for relative size of MD against BL); the second principal and third component placed Malay and South Chinese between Negritos and South Indians. The Negritos possessed larger relative molar and incisor size.

Haeussler *et al.* (1989) compared two South African groups using metric and non-metric dental data and revealed several differences between the two. The San group had more complex occlusal surfaces but were microdontic (small tooth size). Central Sotho dentition was considered mesodontic (medium to large tooth size) but more simplified morphologically. Morphological complexes identified San as having moderate low-grade UI1 (13.5%) and UI2 (24.7%), high Bushman canine (43.1%), low UM2 hypocone reduction (23.3%), high UM2 cusp 5 (55.6%), high LM1 cusp 7 (35.2%), LM1 distal trigonid crest (7.1%), and LM2 deflecting wrinkle (5.3%), lack of reduction of LM1 and LM2 cusp number, high LM2 Y-groove and very low UM1 Carabelli trait. Central Sotho was characterized as simple except having high C7 (71.3%), and moderate Carabelli trait (41.0%). In conclusion, both groups did not appear to belong to Asian or European groups based on calculation of indices of similarity. This index was calculated as the sum of the differences between frequencies for each trait, divided by the number of traits, and subtracting from 100:

$$\text{Index of similarity} = 100 - \frac{\Sigma\left(\left|f_{ia} - f_{ib}\right|\right)}{N}$$

f_{ia}, frequency of trait i in sample a; f_{ib}, frequency of trait i in sample b; N, number of traits.

There is no doubt that dental traits (metric and non-metric) are useful for studies of population variations and affinities. To meet forensic requirements, which is to predict or estimate individual ancestry, statistical probability is necessary (Dahlberg, 1963). This prediction is actually the reverse process to the traditional anthropological process. For anthropological studies the strategy is to build a normal standard variation for a particular group of people so that the divergence or affinity can be assessed, whereas the forensic identification process is interested in predicting unknown individual ancestry with certain probability against the normal standard variation recognising individual variation effects within the populations. Taking into consideration within group variation and the nature of dental traits, statistical probability should provide an estimation rate. The further the separation between groups, the better estimation rate can be expected. Larger within group variation or intra-individual variation, the more overlap of dental trait distribution between groups meaning more misclassification in the prediction.

Classification and statistical predictions have been shown to be successful for several populations. Haeussler *et al.* (1989) applied discriminant function analyses to two South African populations. Multivariate analyses confirmed the difference between the two groups. The classification rate for San and Central Sotho using metric data was correct in 82% of

applications. Eight variables were selected from 24 original variables; MD UI2, UC, UP2; BL UP1, UM1, UM3; crown surface areas on UI1 and UM3 (maxillary teeth only). Even though success rates were considered high, practical application in forensic situations would be limited to adults only with the inclusion of M3. Another aspect requiring caution would be the influence of differing sample sizes, with the Central Sotho sample being 2.5 times larger than the San group. Bias could result in the estimation of discriminant function and the classification of samples from these data.

Matis and Zwemer (1971) utilized discriminant function analysis on combined data, tooth morphology and size which they defined as odontognathic data, to predict ethnic discrimination and classification among United States Indian and Eskimo groups. The odontognathic data used were the depth of the incisor palatal fossa, four grades of Carabelli trait, five grades of mandibular tori, the buccolingual diameter of upper second premolars, buccolingual diameter of upper first molars, proportion of buccolingual diameter of upper second premolars and upper first molars, mesiodistal diameters of central and lateral incisors and the difference of lateral and central mesiodistal diameters. From step-wise discriminant function four variables were significant in contributing to maximum separation between groups, namely the buccolingual diameter of upper second premolar, upper first molar, shovel depth and frequency of Carabelli trait. The results revealed the Eskimo group to be markedly separated from the other Indian groups. The success rate of correct classification was very high, almost perfect, for Eskimo and American Indians at 97%. However, poor for classification rates for within American Indian tribes (Pima, Navajo, Apache and Papago) were found, at less than 60%.

Similar research by Chiu and Donlon (2000) using tooth size measurements of MD and BL of upper and lower teeth (except M3) was very successful in classifying Mongoloids and Caucasians, at 93.9%. The average success rate could have been inflated due to the same sample being used to generate discriminant function and to predict group membership. However, it is worth comparing samples used in this study with the scenario in Malaysia. The major ethnic groups living in Peninsula Malaysia are Chinese (mainly originated from South China), Malays (from Peninsula Malaysia, Sumatra and Java) and Indians (mainly from South India) (Tratman, 1950). The exploration of alternate methods of identification can be expected to be highly successful between the Indian and Chinese/Malays who make up the Indoeuropean and Mongoloid/Southern Mongoloid group respectively although the discrimination between the Chinese and Malays may be problematic. If we accept the studies of Turner (1990) and agree that Mongoloids can be successfully subdivided into Sinodont and

Sundadont, we may expect some promising results for the Malaysian populations. However, cautious remarks from a number of authors including Matis and Zwemer (1971), Palomino *et al.* (1977), and Scott and Turner (1997) should be taken into consideration. They suggested that dental traits (tooth morphology and size) are useful for discrimination at the broad level (tribal and race differentiation) but less sensitive for lower levels of differentiation such as intra-tribal differences.

In this thesis, I will take the opportunity to test whether the dental characteristics of recent Malaysian populations, consisting of Malays, Chinese born in Malaysia, Indians born in Malaysia and Negritos of Peninsula Malaysia, parallel findings from Turner (1987, 1990), Hanihara (1992b), Hanihara and Ishida (2005), Matsumura and Hudson (2005) and their population history of migration. Subsequent investigations will involve searching for dental variables that are suitable for discriminating between these groups (group level) and testing the classification rate (individual level) using discriminant function analyses. Currently, there are no published reports of any attempts to compare the dentitions from the four Malaysian ethnic groups statistically, leading to the generation of formulae for human identification.

2.8 *Reliability of measuring and scoring metric and non-metric dental variables*

Reliability can be viewed from two aspects: validity and reproducibility or reliability (Houston, 1983). Validity refers to the actual value derived from tooth measurements or trait observations that carries underlying biological meaning. For anthropological studies, maximum dental crown size is considered to be an anatomical feature that represents maximum genetic potential. Thus, samples for studies of tooth size must be carefully selected so that measurements will reflect biological meaning only. Flawed casts, lesions and restorations that obscure landmarks and traits must be excluded from measurement or recording. Another source of serious bias that can affect the validity of biological meaning is distortion of study casts due to problems with the impression technique, material and manipulation, and model fabrication. Proper adherence to protocols and manufacturers' instructions is mandatory to preserve the validity of non-metric observation and tooth measurements.

Anatomical landmarks for metric dental anthropological studies should reflect the maximum diameter of the tooth, as proposed by Moorrees (1957). In contrast, the landmarks often used in clinical studies are the contact points that do not necessarily reflect the maximum diameter of the tooth. It is, therefore, important to choose appropriate measurement definitions that are consistent with the objectives of the study. The same consideration applies to selection

of crown traits. The selection of dental traits to characterize and study inter-population distance must utilize heritable traits, as the validity of the study relies on the assumption that varying expression of dental traits reflects underlying genetic variation.

Reproducibility must be assessed for both systematic and random ('accidental') errors (Hunter and Priest, 1960; Houston, 1983). The method of double determination refers to the approach where a sub-sample is randomly selected from the study sample and re-measured using the same instrument, measurements' definitions and conditions. If readings from the sub-sample are consistently larger or smaller on a second occasion than the first readings, the difference is called systematic error. An example would be using different calipers for measuring tooth size in a sample and its sub-sample. If the beaks were not exactly identical in their sharpness, a tendency for systematic error would be unavoidable, for example where a set of calipers with thicker beaks may consistently under-measure tooth size in the sample or sub-sample because they cannot be placed fully into the interproximal areas between teeth.

Random error can occur in an experiment in either direction-both above and below the true value. Not uncommon in tooth metric and non-metric studies, random error may arise from inconsistent definitions (Houston, 1983) or a difficulty in determining the degree of expression of morphological traits due to subjectivity in grading scales. Even when using standard dental plaques (e.g. Dahlberg, 1956; Turner *et al.*, 1991) consistent readings can be difficult to achieve. Non-metric studies on Carabelli trait by Pinkerton *et al.* (1999) initially used eight ranked scales adapted from Dahlberg (1956) but the researchers found that experimental errors were high, in the range of 30-40%. The errors fell within an acceptable range of 11-16% when a modified three-ranked scale was used of absent, concavity and convexity. These results illustrate the difficulty in recording non-metric traits consistently.

There are several methods and statistical methods commonly used in reliability studies (non-metric and metric). Both systematic and random errors need to be assessed in every experiment utilizing any type of measurement (Townsend, 1985). Houston (1983) provided evidence that even when random error was small, systematic error could still be significant. The reason behind this can be understood by considering the formula for the paired t-test used for assessing systematic error.

where:

$$t = \frac{\text{Mean difference}}{\text{S.E.}}$$

with n-1 degrees of freedom, where n= number of pairs, and S.E. is the standard error of mean difference

From a mathematical point of view, the inverse relationship between the t-value and the S.E. of the mean difference implies that a large S.E. due to large random errors will tend to reduce the t-value, making systematic errors difficult to detect. As the power to detect any differences is influenced by sample size and the level of significance (Houston, 1983; Townsend, 1985) it is suggested sub-samples for double determinations should not be less than 25. In addition, t-tests require data to be normally distributed. According to central limit theorem, with an increase in sample size, mean values will approach a normal distribution reinforcing that a sample size of more than 25 is reasonable.

Random error is commonly assessed using the Dahlberg statistic, or the standard deviation of a single determination (Dahlberg, 1940). This statistic is sometimes referred to as the technical error of measurement (Carr *et al.*, 1989). The formula for the Dahlberg statistic is as follows:

$$\{(\Sigma\, d^2)/2N\}^{1/2}$$

The square of the Dahlberg statistic is referred to as the error variance, Se^2, ie:

$$Se^2 = (\Sigma\ d^2)/2N$$

where d is the difference between the first and second readings and N is the number of samples for double determination (Houston, 1983; Townsend, 1985). The error variance can be expressed as a ratio of the observed variance, then expressed as a percentage, as follows:

$$(Se^2/So^2)100\%$$

Values less than 10% for this ratio are generally accepted to indicate good reliability.

It is worth noting the work of Nichol and Turner (1986) using 47 graded and discrete morphological traits of the dentition and jaws of 50 Kodiak Island Eskimo dental casts. They assessed reproducibility using frequencies of discordance (in percentages) and highlighted several important findings relating to the discordance in agreement:

1) The percentages of discordance improved with practice
2) Higher discordance was noted with longer periods of time between the two readings
3) Generally discordance for present-absent classifications was lower than when considering all grades of expression. Mean scores for present-absent classification ranged from 10.2%-11.8% whereas variant scoring ranged from 25.9-29.4%.
4) A discrepancy of more than one grade occurred in more than 10 percent of cases in any of three occasions for tuberculum dentale UI1,UI2; distal accessory ridge UC, LC; deflecting wrinkle LM1 and protostylid LM1. According to the authors

these traits were considered problematic in terms of "imprecise observational technique, recording error, or difficulties with standard itself".

5) The scoring discrepancies occurred at random.

Therefore, it is important in studies of non-metric traits for the balance between validity and reproducibility to be maintained, particularly when deciding to use existing grade scales or modified grading lesser scales. More biological information can be derived from grading scales than dichotomous type data, however, due to difficulties inherent in the 'in-between' expressions when using grade scales less discordance would be anticipated when using fewer categories e.g. three or four categories rather than six to nine categories (personal communication, Kondo, 2004). In other words, there is a trade off between increasing the amount of potentially biologically meaningful information (by using many categories of expression) against minimizing the extent of inherent errors (that are reduced generally by using fewer categories).

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Chapter 3 Materials and methods

3.1 Materials

3.1.1 Sample collection and sample distribution

This cross-sectional study is based on records collected from four different ethnic groups living in Malaysia; Malays, Chinese, Tamils and Orang Asli. Dental models and other records of Malays, Chinese and Tamils were collected from secondary school children in Kelantan State (Kota Bharu, Kuala Krai and Tanah Merah) and Perak State (Ipoh) (Figure 3.1). Records for the Orang Asli were collected from the New Resettlement Plan Air Banun, Banding Perak (RPS Air Banun). The Orang Asli who participated in this study belonged to the Jahai tribe (subgroup of Negritos) who are only found in the northern part of the Peninsula of Malaysia.

3.1.1.1 Sample collection from schools

Nine secondary schools in Kelantan were involved in this study. Two of the nine schools were known to have Chinese majorities (the only schools in Kelantan with Chinese majorities) and another two schools were known to have higher percentages of Tamils compared with other schools in Kelantan. These two schools were situated in Kuala Krai and Tanah Merah. The other seven schools in Kota Bharu comprised a majority of Malay students. Since the Tamil population in Kelantan is very small, additional samples were collected in Ipoh, Perak samples from an additional four secondary schools.

Records collected included standardized extra-oral photographs, both lateral and frontal views; measurements of weight and height; dental impressions from which dental models were constructed; intra-oral photographs; oral examinations including charting of teeth present, and students' demographic details. This study reports on observations and measurements from the dental models. Intra-oral photographs were also used in conjunction with dental charting to assist with assessing some features on the dental models, for example groove pattern and restorations.

The selection of schools was based on approval obtained from the principal, the distance from Hospital Science University (for schools in Kelantan) and the ethnic composition of students. Initial discussions with school principals aimed to fit examination times with school schedules. The main concern from schools was possible interference with classes that might result from the study. To minimize interruption to students, an appointment was made prior to

each visit. Procedures were conducted in the mobile clinic that has two dental chairs and space for a dental technician to work.

Inclusion criteria set for this study were: consent from parents, the children were healthy with no history of congenital craniofacial anomalies; no history of craniofacial treatment; and no history of mixed marriages for the past three generations. For the study of dental casts, observations or measurements were not made if there was evidence of flaws in the casts, dental caries, restorations, attrition, abrasion, erosion or any situation that obscured a feature such as calculus (Appendix 3.1). Partially erupted teeth were also excluded if features could not be observed clearly and recorded. For example, the lower right first molar (tooth 46 Federation Dentaire Internationale (FDI) notation) was studied to record groove pattern, tuberculum sextum, tuberculum intermedium and measurements of mesiodistal and buccolingual crown dimensions. If casting flaws involved the occlusal grooves of this tooth or thick calculus was present at the lingual cervical region, then groove pattern and buccolingual dimension were excluded.

The distribution of samples according to age, sex and ethnicity are given in Table 3.1. All school samples had similar mean ages (15-16 years), with slightly more female participants than male participants in all ethnic groups, except the Chinese. Young adolescent groups were chosen due to their minimal tooth attrition and dental decay. Several participants from one school, aged 13 years old (Form 1), still had partially erupted second molar teeth therefore, at this school only student in Forms 2 and 4 who had reached ages between 14 to 17 years were included. In other schools, especially those with a Chinese majority, children from Form 1 were included in the study. As can be seen from Table 3.1, even after inclusion of volunteers from Form 1, the Chinese sample contained the smallest sample size compared with the other two ethnic groups.

3.1.1.2 Sample collection from Orang Asli resettlement area

The New Resettlement Plan (RPS) Air Banun, Banding Island, Perak is situated at Banjaran Titiwangsa, a mountainous area which forms the backbone of the Peninsula of Malaysia (Figure 3.2). There are 17 villages in the RPS Air Banun, eight of which were visited during a seven-day trip. Several weeks before the research project was conducted, there were two meetings held with the manager, staff of RPS Air Banun, officers from Department of Orang Asli Kuala Lumpur, and RPS Air Banun primary school representatives. The meeting was held at RPS Air Banun to discuss the logistics of the project including promotion, facilities and research layout. We were grateful to the manager and staff at RPS Air Banun for allowing our team, which comprised 26 people including four females to stay in RPS Air Banun center. They were two

radiology technologists, two dental technicians, one biology lab technologist, a medical nurse, two dentists (for the first two days), cook (drivers and office boy), a dental nurse, three dental surgery assistants and a research assistant who assisted in record collections. On the first day, an opening ceremony was held at the school compound in the morning. Research commenced after having lunch with approximately 150 locals from several villages.

Home visits were used to meet every family in each village to explain the project and invite them to participate in the study. At the same time, we took the opportunity to distribute a toothbrush and toothpaste to every child in the villages. Before entering and meeting villagers, it was important to obtain permission from Tok Batin (the leader of people).

The home visits started from Kampung (Kg) Sungai (Sg) Banun (13-1-2003); Kg Pulau Tujuh and Kg Sg Tekam (14-1-2003); Kg Semelor (15-1-2003); Kg Sg Raba (16-1-2003); Kg Pengkalan Permai, Kg Desa Permai and Kg Desa Damai (17-1-2003).

The journey from the RPS center to Kg Semelor, Kg Sg Tekam and Kg Pulau Tujuh, which are situated at the peak of the mountain, took one hour in 4-wheel drive vehicles. The home visits and research project were conducted concurrently in these three villages. Records from other villages (Kg Air Banun, Kg Sg Raba) were collected at the RPS center from 8 a.m. until 12.00 p.m. For safety reasons, transportation was provided for participants who attended after dark.

Records from the other three villages, except radiographs, were collected in Kg Desa Permai. One of the residents in that village allowed us to use his house as a temporary clinic. Radiographs were only obtained in the mobile dental clinic. Since many villages are situated in high areas and the road was not suitable for a 16-tonne bus, the mobile clinic was kept at the RPS center. All participants who gave consent were transported using the 4WD vehicle except those from Kg Air Banun and Kg Sg Raba who attended after hours.

Additional records were collected such as blood samples and radiographs (lateral cephalograms and orthopantomographs) but these will not be considered in this thesis. This project was considered exploratory since samples had previously been collected from only one tribe, and no other similar project had been conducted on any of Orang Asli tribes in Malaysia. There will be future research trips that will include several other tribes at the settlement. The distribution of participants is given in Table 3.1.

The mean age of participants was approximately 30 years for both sexes, however, there was a wide age range from 15-45 years for male and 16-43 years for female samples. The sample size in both sexes was approximately equal with the number of female participants slightly exceeding males.

For the Jahai group (Orang Asli), only older people participated in the study. Even during home visits we only met young adolescents infrequently. Many of them worked with a logging company at the top of the mountain and some of them went deep into the jungle for several days collecting rattan, herbs and other crops.

In summary, reasonable statistical power for the study was anticipated for the Malay, Chinese and Tamil samples, given their relatively large sample sizes. On the other hand, the Jahai sample size was quite small and included older participants who were expected to have interproximal and occlusal attrition that might obscure some features and lead to exclusion (thereby giving a smaller sample size). The sampling method was not fully randomized, however, there was no bias towards certain dental morphological traits or tooth size in the sample selection.

3.1.1.3 Ethical clearance

Ethical clearance was sought from both universities, The University of Adelaide and Universiti Sains Malaysia. Ethical clearance from The University of Adelaide was obtained on 11th April 2002; Project no: H-09-2002 (Appendix 3.2). The ethical clearance was extended in 2003 (Appendix 3.3). The Research & Ethics Committee, School of Medical Sciences, University Sains Malaysia approved the application dated 16th October 2002; USM/PPSP/Ethics Com./2002(91.2(6)) (Appendix 3.4). The main ethical issues to address in this study were to obtain agreement from the Department of Education and school principals, as well as parents, since the students who participated in the study were all under 18 years of age. Separate applications were submitted to Department of Education, one in Kelantan and the other in Kuala Lumpur and Perak. The first agreement was received on 8th August 2002 from the Department of Education in Kelantan (Appendix 3.5) and the second agreement was received on 26th November 2002 from Kuala Lumpur and 2nd January 2003 from Perak (Appendix 3.6 and 3.7). The students involved in the study were from Forms 2 and 4, *ie* from ages 14 to 16 years. The reason for this was that agreement from Department of Education was conditional on the participation of non-exam year students only. Another condition was that permission had to be obtained from parents prior to commencing the research. All Form 2 and 4 students from selected schools were given three forms containing information sheets, consent and reply forms (Appendix 3.8, 3.9, 3.10,). Information sheets described the background of the research to parents and every student was given a week to allow their parents to fill out all three forms. Reply forms contained questions about students' demographical details, ancestry, past dental and medical history, and weight at birth. Some schools allowed a 30-minute period to explain the

background of the research to the students, and how to fill in the forms that were distributed to every student before the briefing. In other schools, the three forms were distributed and collected by a designated teacher. Only those students who met the criteria (healthy, pure ancestry, and with no history of any craniofacial reconstructive surgery) were given appointments.

Separate ethical clearance was also required to conduct a research project in the RPS Air Banun region. This was endorsed on 20th November 2000 between the Department of Orang Asli in Kuala Lumpur and School of Dental Sciences (Appendix 3.11). Subsequently, an application for ethical clearance was submitted to the Universiti Sains Malaysia and was approved under grant number 304/PPSG/6131145. This approval covered collection of records such as blood samples, radiographs, photographs, dental examinations, and dental impressions to make models, as well as measurements of weight and height.

Two Orang Asli volunteers from RPS Air Banun (trained by the Health Division, Department of Orang Asli) assisted throughout the project. They explained and translated information for those participants who were not able to read or write regarding the content of information sheets and consent forms (Appendix 3.12, 3.13).

Throughout a 7-day period, in addition to the the two health volunteers, officers from the Department of Orang Asli were always present to assist and monitor the project. This was to ensure that no violation or misconduct occurred against the Orang Asli. Only those who gave written consent and met the inclusion criteria participated in the study.

Table 3.1 Sex and age of participants in the four study samples

Ethnic group	Sex	N	Mean (years)	SD
Malays	Females	167	15.6	1.2
	Males	126	15.1	1.3
	Total	293	15.4	1.3
Chinese	Females	88	14.5	1.3
	Males	90	14.7	1.5
	Total	178	14.6	1.4
Indians	Females	131	15.8	1.4
	Males	121	15.6	1.3
	Total	252	15.7	1.3
Negritos (Jahai)	Females	33	28.3	8.2
	Males	34	30.5	13.1
	Total	67	29.4	10.9
Total	Females	419	16.4	4.4
	Males	371	16.6	6.1
	Total	790	16.5	5.2

N, sample size; SD, standard deviation

Figure 3.1 Map of the Peninsula of Malaysia showing the location of schools and New Resettlement Program area

school locations

New Resettlement Program (RPS Air Banun)

Figure 3.2 Orang Asli distribution according to locations in Peninsula of Malaysia

Jahai, one of the subtribes of Negritos live in the mountainous area near Banding Perak.

3.2 Methods

3.2.1 Procedures used in obtaining impressions and constructing dental models

As it was essential that the final dental models had minimal distortion, strict adherence to manufacturer's instructions for both impression materials and casting stone was mandatory. The dental technician assisting this project was briefed on the protocols for model casting. There were two sources of distortions: clinical and laboratory procedures. It was important to remove impressions from participants' mouths with a snap action and the tray used needed to be rigid. Alginate powder (Litochrome Type I) and water for mixing were measured using the measurement scoop provided by the manufacturer. The dental assistant was briefed to make sure that the alginate powder was packed properly into the scoop and sufficient water was used. The ratio of powder to water was 1:1. For upper impressions three scoops of powder were used and for lower impressions two scoops were needed. An Alginmix machine was used at a standardized setting for 8 seconds to achieve a smooth homogeneous texture of alginate. Impressions were checked for evidence of tears, any dislodgement from the tray and bubbles before proceeding with casting. If flaws occurred, impressions were repeated with permission from participants. Trays were marked with identification numbers before transfer to the dental technician.

The time between impressions being removed from the mouth to casting with dental stone ranged between 5-10 minutes. Impressions were rinsed thoroughly under running water to remove saliva, material-alba and any traces of blood. 100 grams of dental stone (Die Keen Heraus Kulzer) and 21 ml water were generally sufficient to pour both upper and lower models for small to medium size dental arches. All procedures of mixing and casting were done in a mobile dental clinic. The ambient temperature in the mobile clinic was cool, so the temperature of the water used for mixing alginate and die stone was quite stable. The die stone was left to set for approximately 60 minutes before carefully removing the models from the impressions. The stone models were then labelled with pencil.

On a daily basis, after record collection at school, all trays used were cleaned and sterilized with a chemical solution, Cydex 2%. Whenever there was a break between appointments, models were based with white plaster at a laboratory in the School of Dental Sciences. Once again, each set of models was correctly labelled to prevent mistakes, and stored in a labelled plastic box.

3.2.2 Measurements obtained from dental models

Measurements on the dental casts utilized maximum diameter of mesiodistal and buccolingual dimensions. The measurement definitions followed Moorrees (1957) who stated that the maximum mesiodistal diameter was measured with the calliper held parallel with the buccal surface of a posterior tooth, and the vertical axis of a single rooted anterior tooth. At the same time the calliper must also be parallel with the incisal edge for anterior and canine teeth, and occlusal plane for posterior teeth. Buccolingual diameter was measured with the callipers held perpendicular to the mesiodistal dimension.

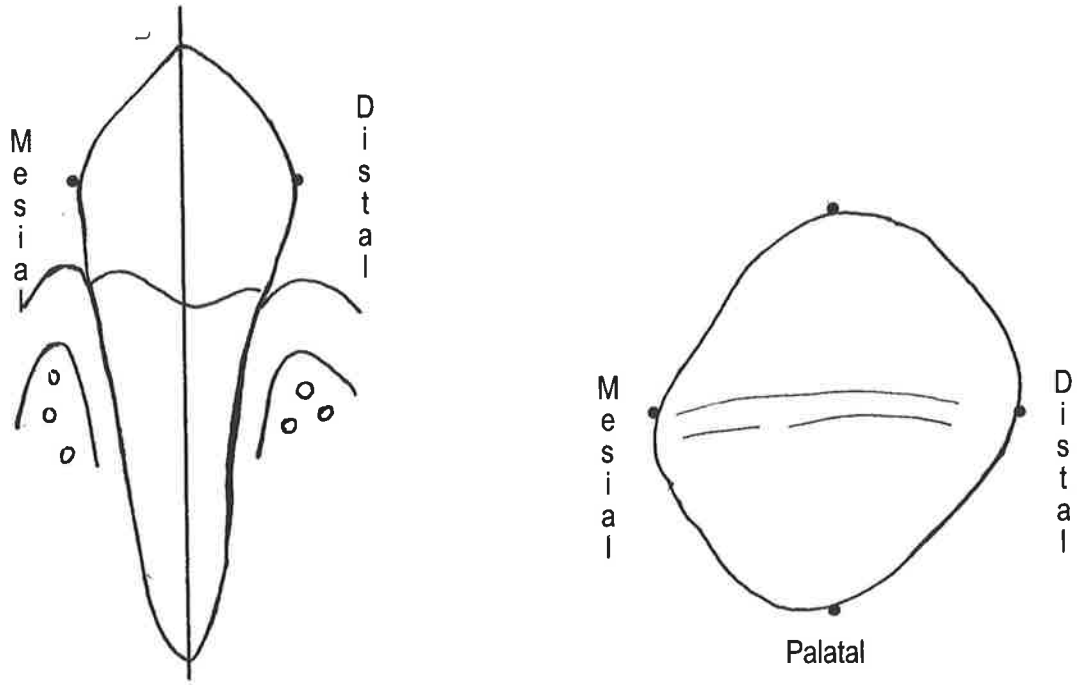


Figure 3.3 Buccal and incisal view of a canine

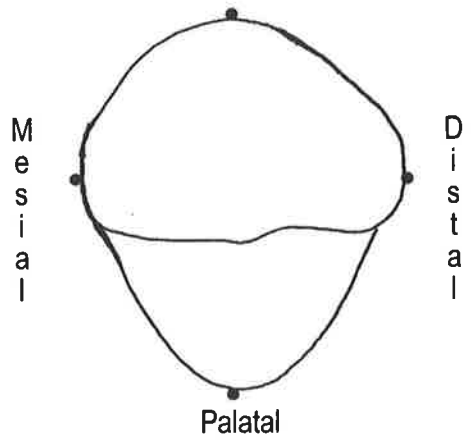


Figure 3.4 Incisal view of an incisor

The vertical line represents the imaginary tooth axial axis. The beaks of the calipers were held parallel to this axis for mesiodistal diameter measurement of canines and incisor (Figures 3.3, 3.4). At the same time the calipers were placed so that the mesial and distal beaks aligned with the incisal edge. The buccolingual or labiolingual dimensions were measured perpendicular to the mesiodistal dimensions. Black dots represent common locations for caliper beaks for maximum mesiodistal and buccolingual diameters.

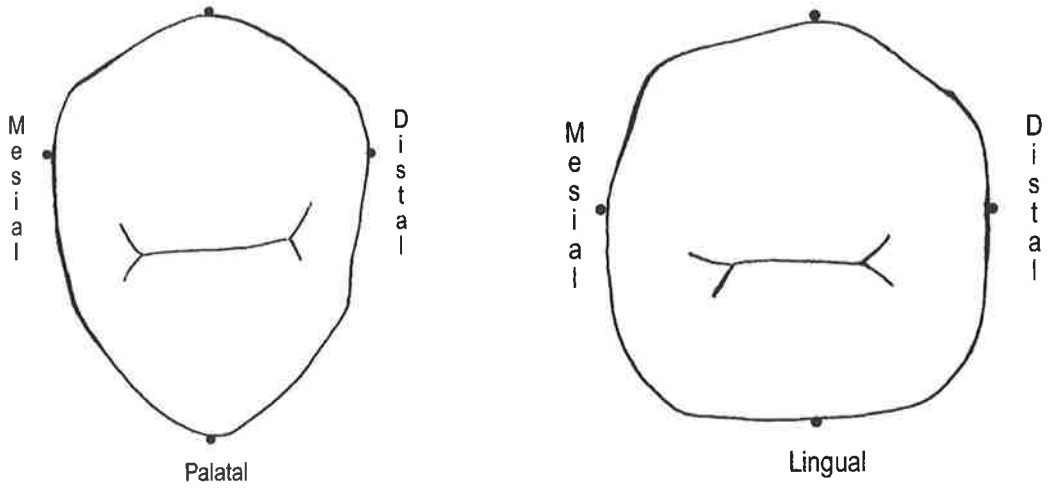


Figure 3.5 Occlusal view of the upper and lower premolar

Figure 3.5 shows common landmarks (black dots) for measuring the maximum mesiodistal and buccolingual dimensions in premolars. The calipers were held so that the beaks were almost parallel with the central groove in the mesiodistal direction while keeping the calipers parallel with the occlusal plane for measuring mesiodistal dimensions. The calipers were held perpendicular to the mesiodistal dimensions for buccolingual diameter measurements.

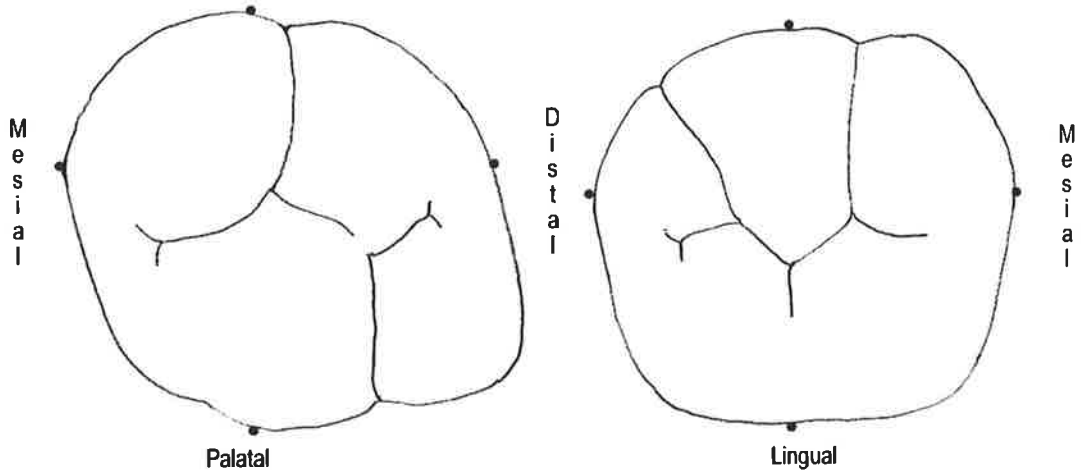


Figure 3.6 Occlusal view of the upper and lower molar

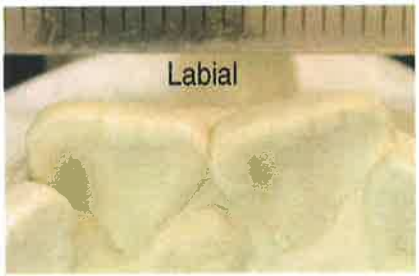
Figure 3.6 shows common landmarks (black dots) for maximum mesiodistal and buccolingual crown diameters for molars. Mesiodistal diameters were measured with the calipers held parallel with the occlusal plane and at the same time the two beaks were inserted at the mesial and distal points of the tooth, so that they were parallel with the buccal surface or the central groove. Buccolingual diameters were measured with the calipers held perpendicular to the mesiodistal dimensions.

3.2.3 Observations on dental morphology

Scoring and observations for dichotomy and grade scale morphological traits were based on the classifications of Arizona State University, Turner *et al.* (1991), Dahlberg (1956) and Townsend *et al.* (1990) are presented in Figures 3.7 to 3.19.

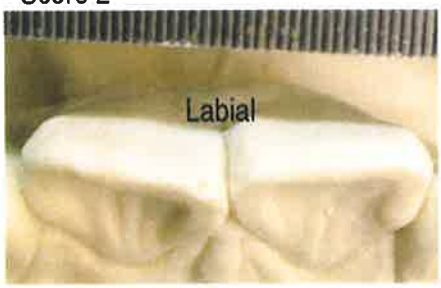
Figure 3.7 Winging on the upper central incisors

Score 1



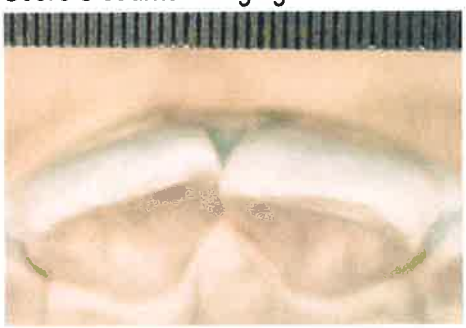
11 & 21

Score 2



11 & 21

Score 3 counter-winging



11 & 21

Score 3 straight incisal edge

11& 21

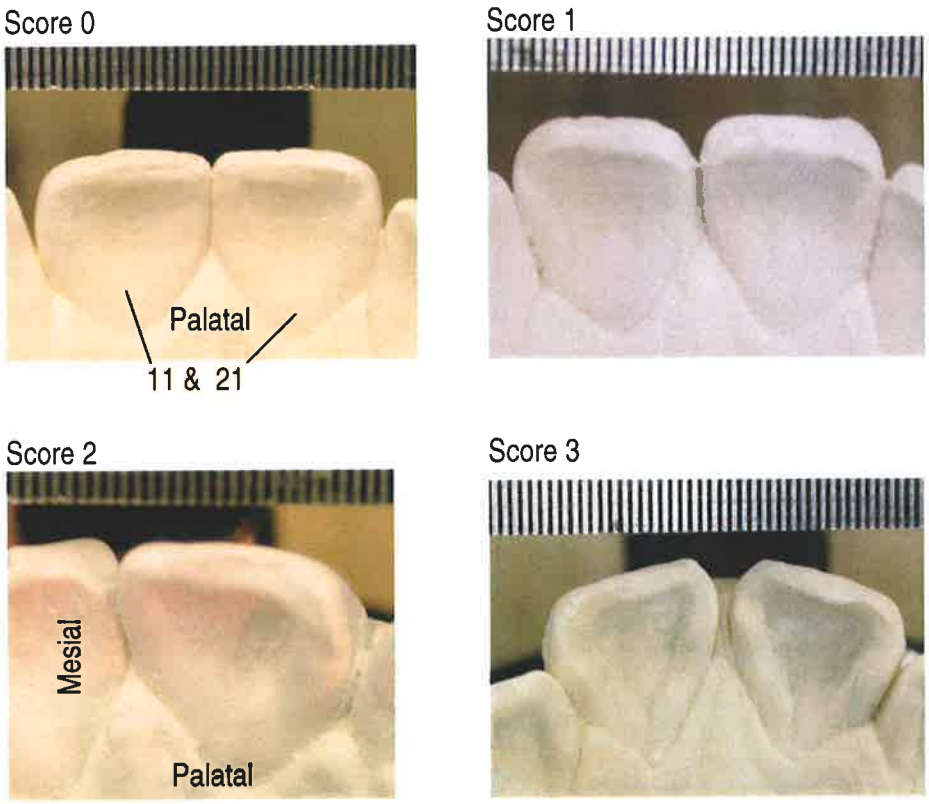
Dahlberg (1958) suggested that winging on the upper central incisors was suitable for population characterization. Winging or "V shape" is thought to have a genetic basis whereas inverse V shape is believed to be due to local environmental effects, such as crowding. The trait is scored according to the following criteria:

Score 1 : the sharp edge of the V pointing to the palate

Score 2: is a unilateral V-shape (only one tooth involved)

Score 3: is represented by an inverse V shape (counter-winging) or a straight incisal edge

Figure 3.8 Shovelling on the upper central incisors



Shovelling occurs when there are prominences on the mesial and distal ridges of upper central incisors producing a shallow scoop on the palatal surface. The trait is scored according to the following criteria:

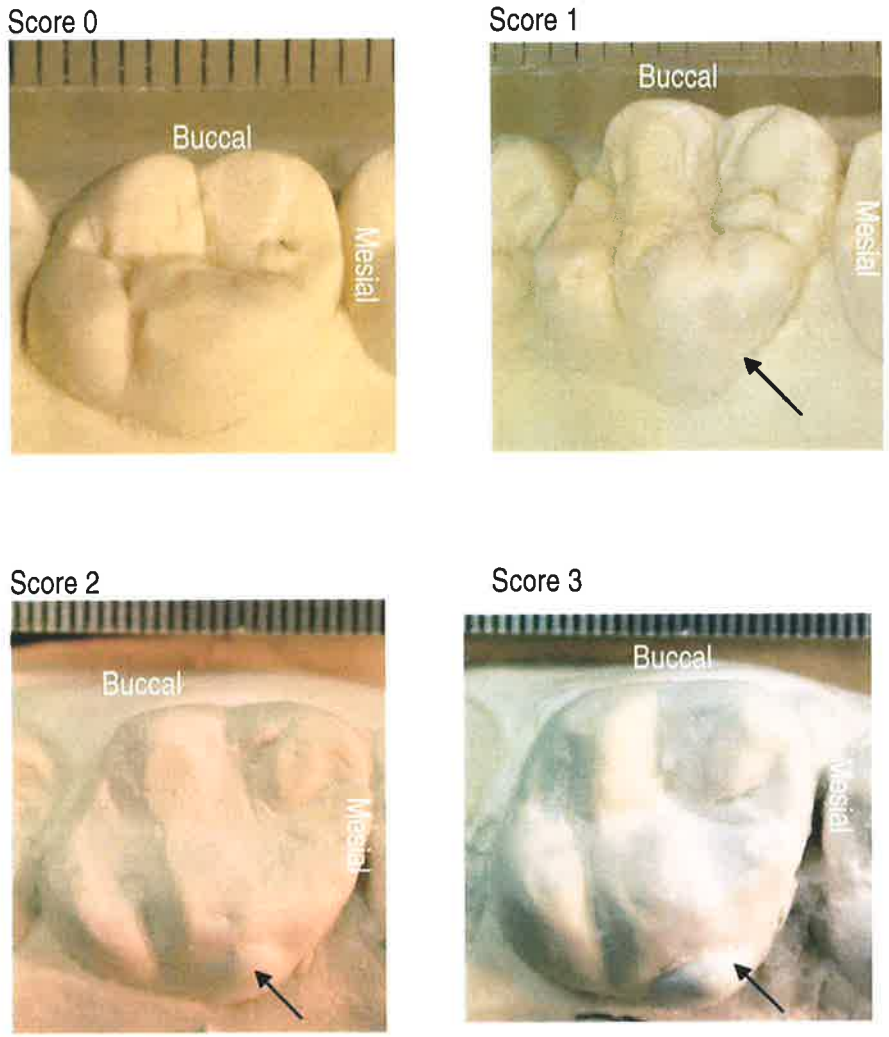
Score 0: is given when there are no prominences observable

Score 1: is given when faint prominences are easily observable

Score 2: is given when the prominences extend halfway cervically

Score 3: is given when the prominences converge cervically

Figure 3.9 Carabelli trait on the upper first molar



Carabelli trait is found on the mesiopalatal surface of the protocone (mesiopalatal cusp). The trait is scored according to the following criteria:

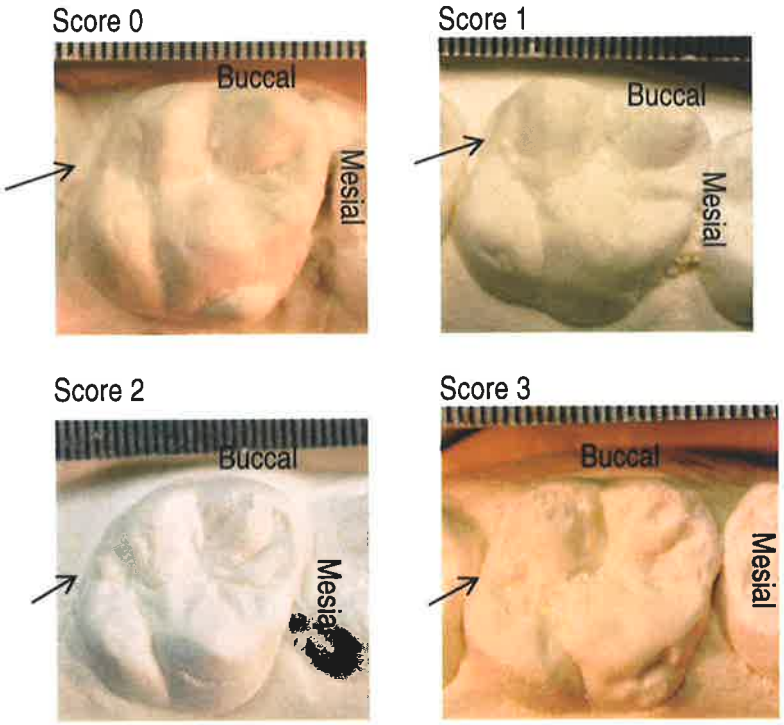
Score 0: indicates a smooth surface of enamel

Score 1: indicates the pit and furrow presentation. The protoconule groove should not be mistaken with the furrow type

Score 2: indicates any well-defined bulging tubercle

Score 3: indicates a cusp with free apex regardless of cusp size

Figure 3.10 Metaconule on the upper first molar



The metaconule is an extra tubercle that is separated from the metacone (distobuccal cusp) and hypocone (distopalatal cusp) by two grooves found on the distal marginal ridge. The trait is scored according to the following criteria:

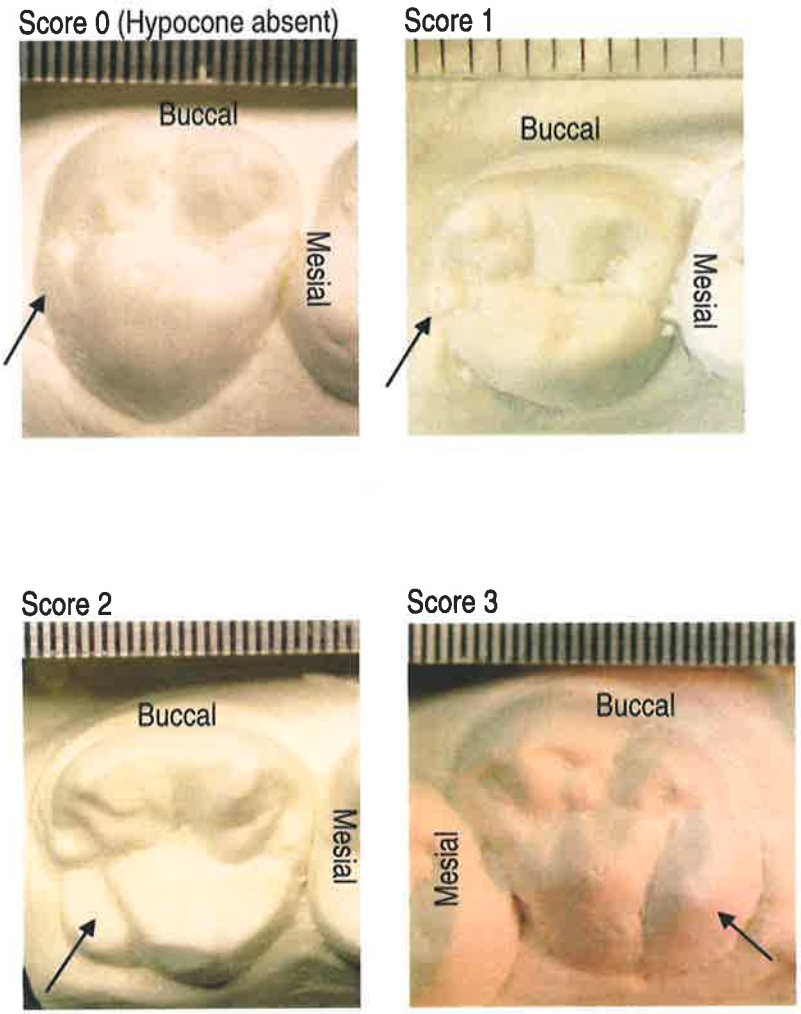
Score 0: has either one groove or is smooth

Score 1: includes a faint cuspule

Score 2: indicates a small cuspule with two grooves running almost parallel

Score 3: is given for a moderate cusp which is larger than in Score 2 and the two grooves are almost parabolic in shape

Figure 3.11 Hypocone on the upper second molar



The hypocone or distopalatal cusp is observed on the second molar. The second molar (being more distal than the first) was chosen because it shows more variation between populations in hypocone reduction. The trait is scored according to the following criteria:

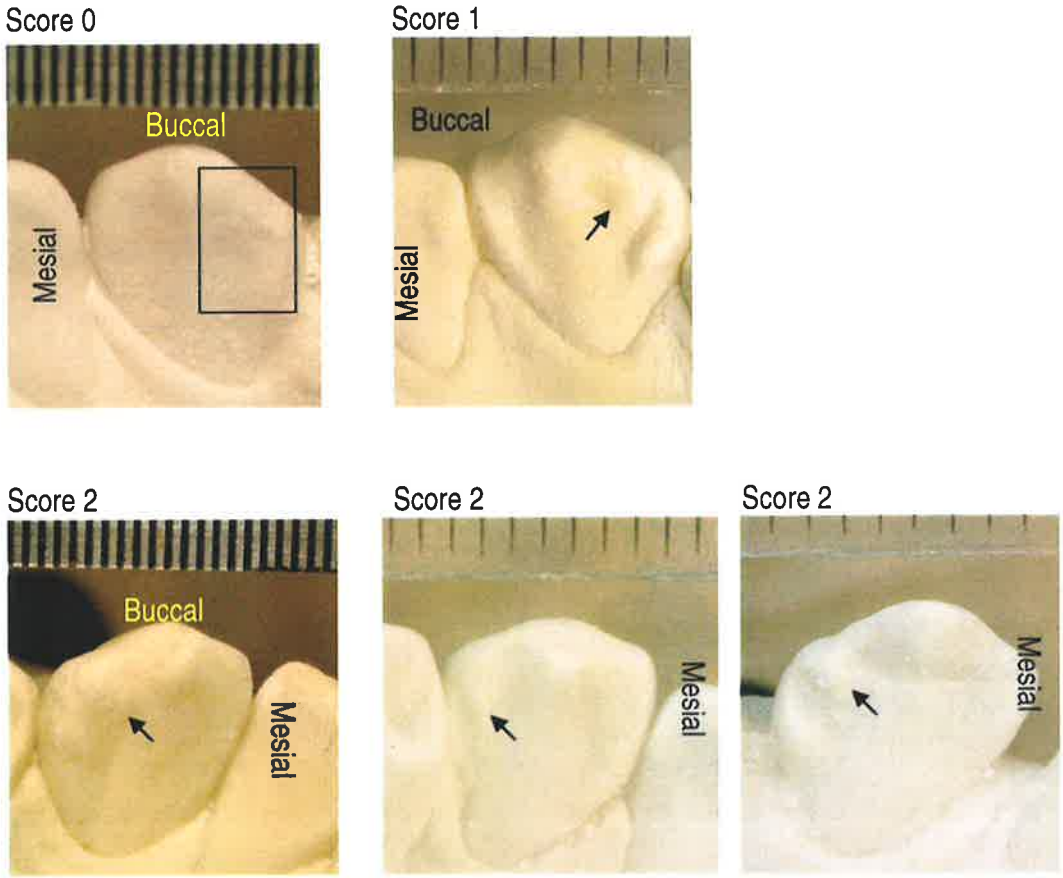
Score 0: indicates total loss of hypocone or ridge, leaving only a three-cusped second molar.

Score 1: indicates a hypocone cuspule

Score 2: refers to a reduced cusp

Score 3: indicates a moderate to large cusp

Figure 3.12 Distal accessory ridge on the lower canine



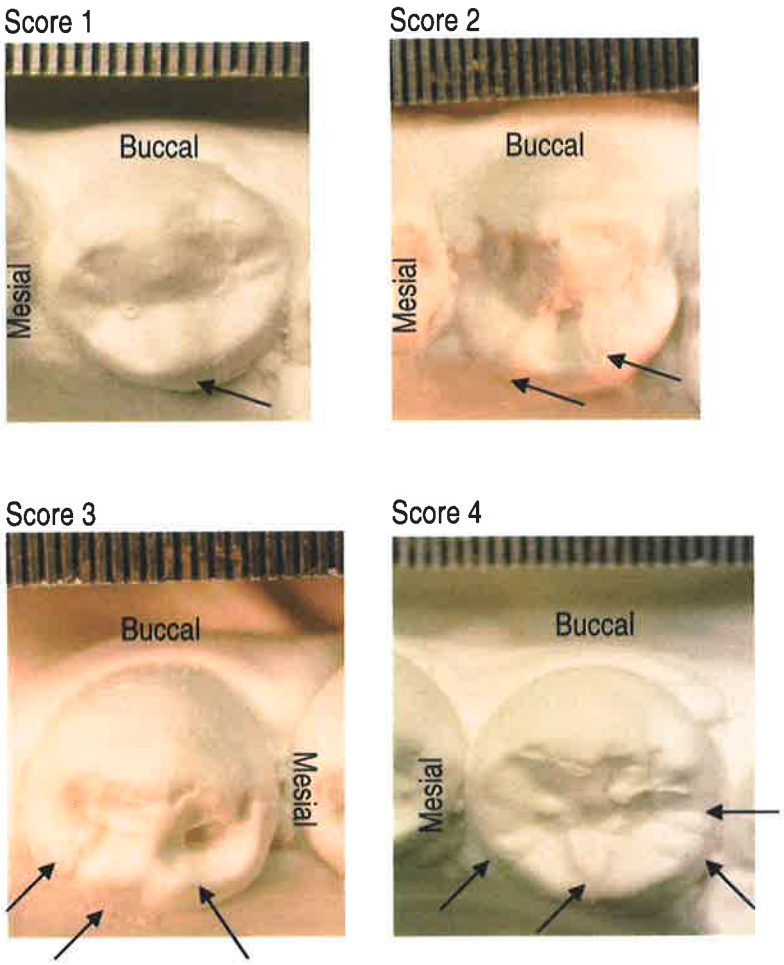
The distal accessory ridge (DAR) refers to a tubercle or ridge between the median and distal ridges on the lingual surface of the canine. The trait is scored according to the following criteria:

Score 0: indicates a smooth surface without any enamel elevation

Score 1: indicates a small and faint ridge

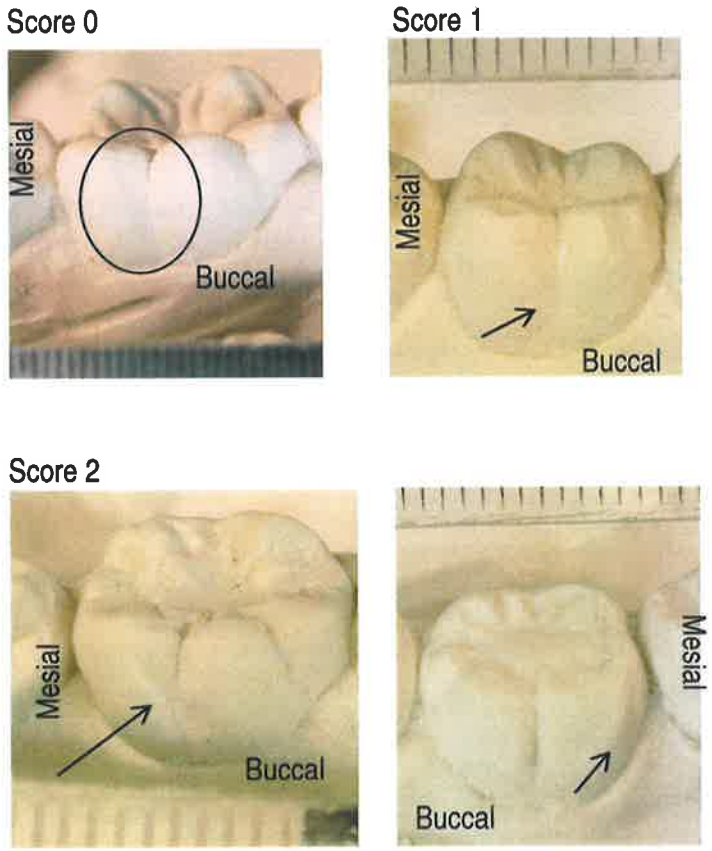
Score 2: indicates a well-defined elevation that is larger than the size in Score 1

Figure 3.13 Lingual cusp number on the lower second premolar



Lingual cusp number is observed on the lower second premolar to show occlusal surface simplification. Cusps are counted even though they are small in size, provided the boundary is well-defined. Scores range from one to four, representing to the number of cusps.

Figure 3.14 Protostylid on the lower first molar



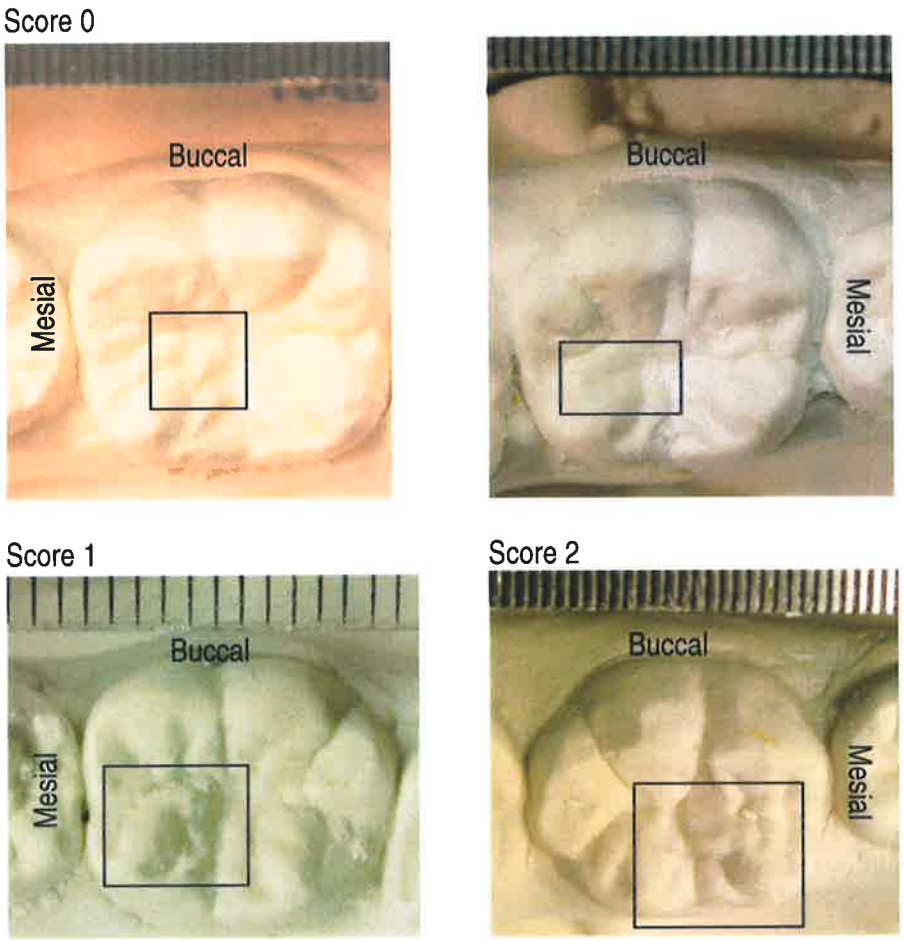
The protostylid is an extra cusp on the buccal surface of the protoconid or mesiobuccal cusp of the lower first molar which involves the buccal groove. The trait is scored as the following criteria:

Score 0: indicates a smooth, straight, buccal groove

Score 1: indicates a pit, distally deviated buccal groove and faint buldging

Score 2: includes a range of tubercular expressions which originate from the buccal groove and include maximum expression of a free cusp

Figure 3.15 Deflecting wrinkle on the lower first molar



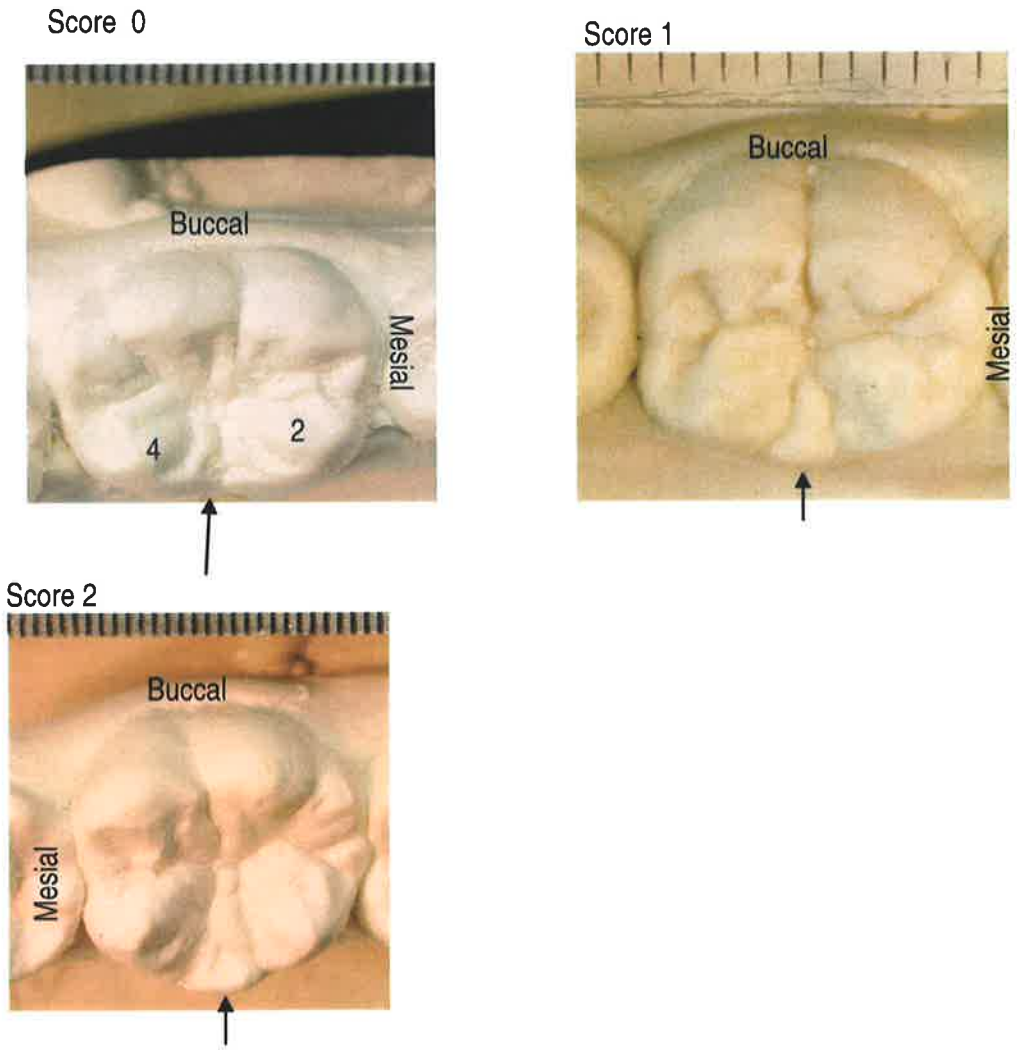
The deflecting wrinkle is located on the metaconid (mesiolingual cusp). The median cusp ridge runs down and deflects in an L-shape towards the entoconid. The trait is scored according to the following criteria:

Score 0: includes straight and constricted median ridge

Score 1: indicates a distally deflected median ridge that does not cross the lingual groove and contact the entoconid

Score 2: indicates a deflected median ridge that is in contact with the entoconid

Figure 3.16 Metaconulid on the lower first molar



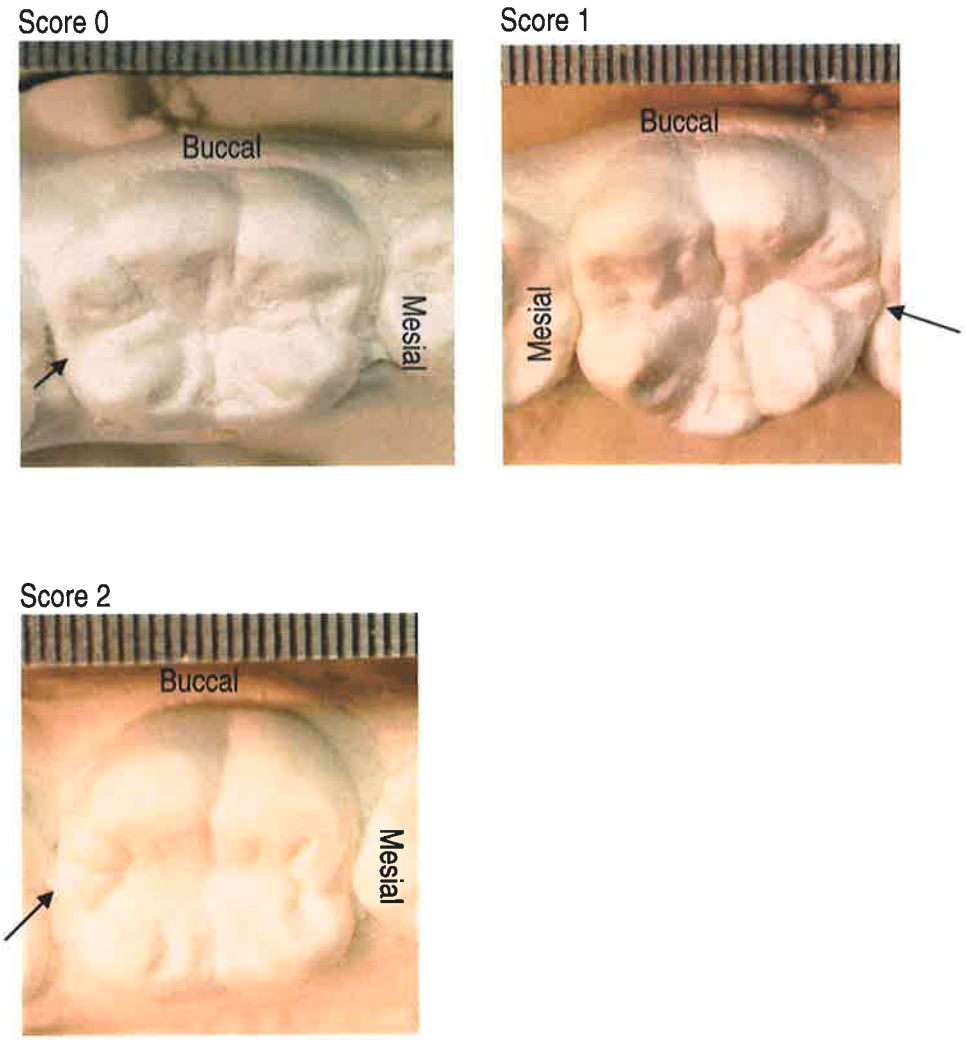
The metaconulid or Tuberculum Intermedium is located between the mesiolingual and distolingual cusps. Any well defined cusp found between these two major cusps will be counted as metaconulid present. The trait is scored according to the following criteria:

Score 0: indicates an absent of cusp

Score 1: is given when the cusp apex does not reach the central groove

Score 2: is given when the cusp reaches the central groove

Figure 3.17 Entoconulid on the lower first molar



The entoconulid, or sometimes called the tuberculum sextum, is an extra cusp on the distal marginal ridge between the hypoconulid (distal cusp) and entoconid (distolingual cusp). On rare occasions, when the distal extra cusp is found on a four-cusped molar and located lingual to central groove it is identified as an entoconulid. The scoring in five-cusped molars is as follows:

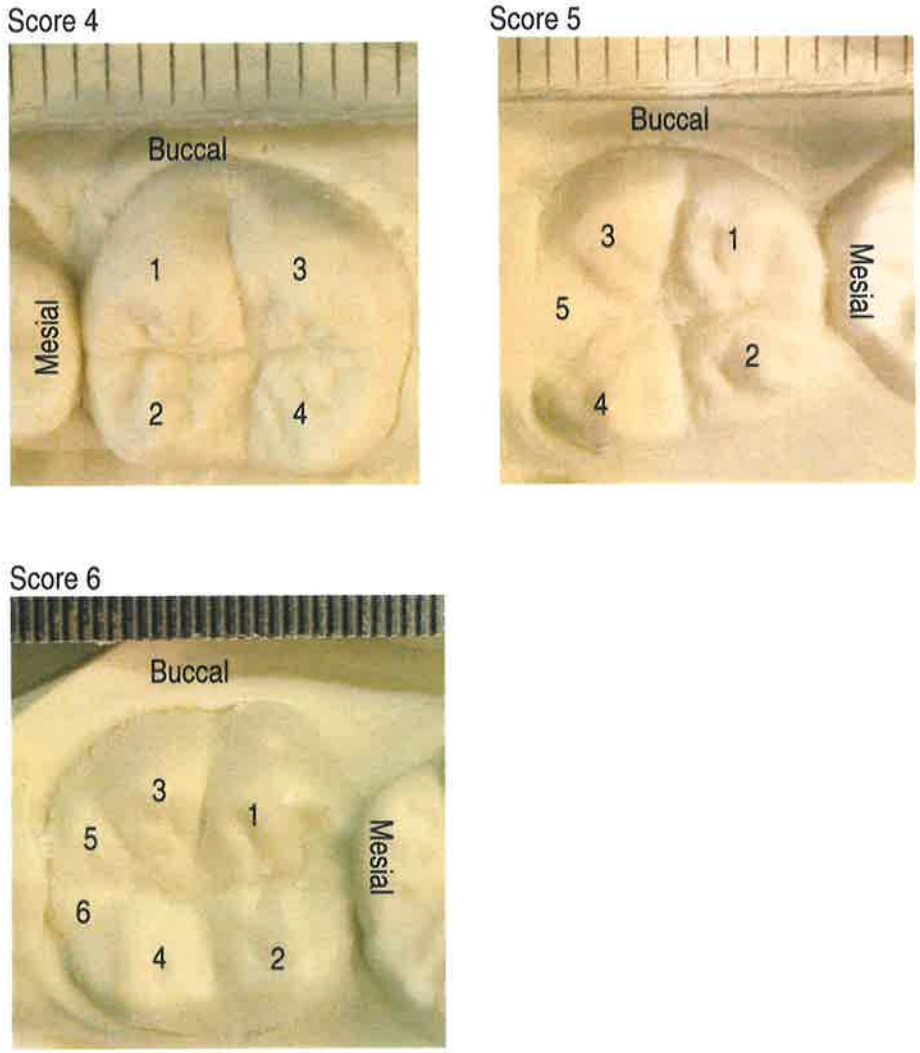
Score 0: indicates a smooth or only one groove can be observed.

Score 1: is given when there is a clear two groove separating hypoconulid and entoconid. The size of entoconulid is smaller than hypoconulid.

Score 2: is given when the extra cusp is approximately equal to or larger than hypoconulid.

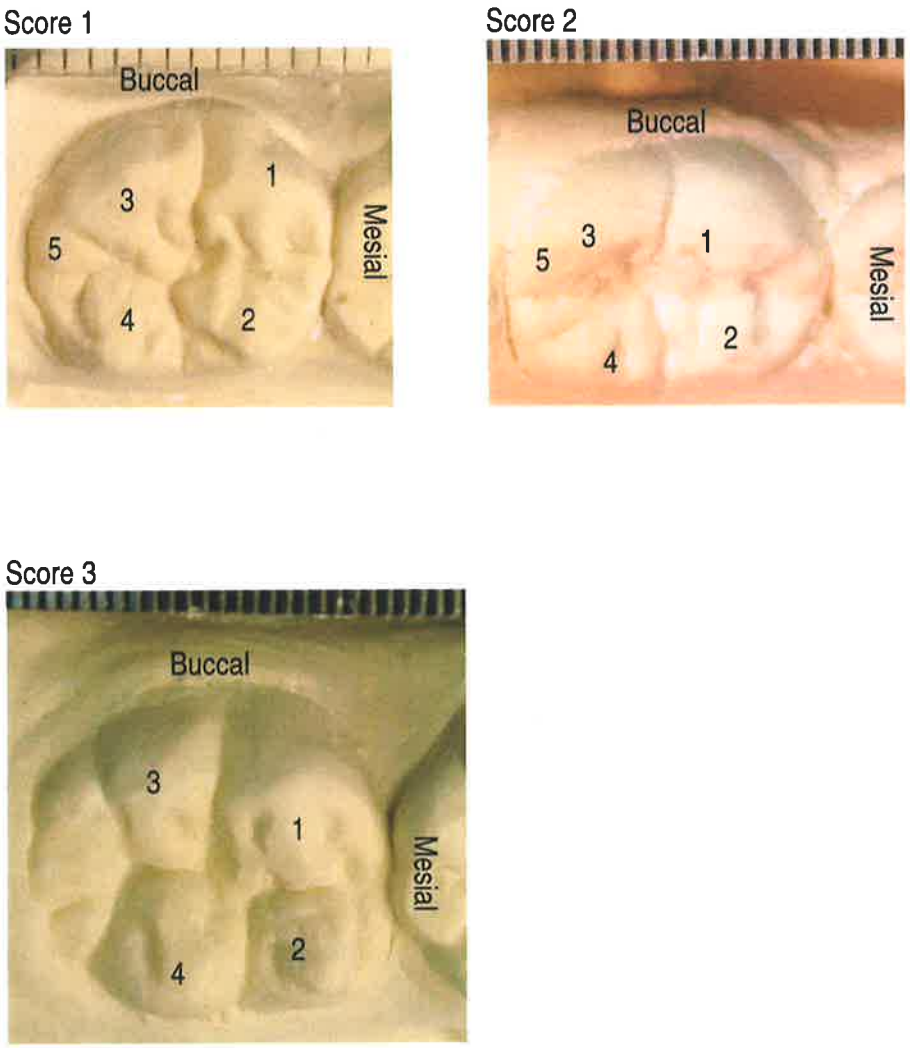
For four-cusped molars, the scoring used direct approximation of the size of entoconulid from the ASU plaque.

Figure 3.18 Lower second molar cusp number



Any free standing and well-defined cusp was counted. The score ranged from 4 to 6.

Figure 3.19 Groove pattern on the lower second molar



Score 1 is given for Y-pattern that is when Cusp 2 is in contact with Cusp 3. The cruciform '+' in Score 2 is given when all cusps 1, 2, 3 and 4 meet in the centre. Score 3 is given for an X-pattern when Cusp 1 is in contact with Cusp 4.

3.3 References:

Dahlberg AA (1956). Materials for establishment of standards for classification of tooth characters, attributes, and techniques in morphological studies of the dentition Zollar Laboratory of Dental Anthropology: University of Chicago.

Dahlberg AA (1958). Rotated maxillary central incisors. *J Japan Orthod Soc* 17:157-169.

Moorrees CFA (1957). The Aleut dentition. Cambridge: Harvard University Press.

Townsend GC, Yamada H, Smith P (1990). Expression of the entoconulid (sixth cusp) on mandibular molar teeth of an Australian Aboriginal population. *Am J Phys Anthropol* 82:267-274.

Turner CG, Nichol CR, Scott GR (1991). Scoring procedure for key morphological traits of the permanent dentition: The Arizona State University Dental Anthropology System. In: Advances in dental anthropology. MA Kelley and LS Larson editors. New York: Wiley-Liss, pp. 13-31.

Chapter 4 Odontometric variation in Malaysian populations

4.1 Introduction

Odontometry has been used in studies of human evolution, genetics, developmental homeostasis, population affinities, forensic odontology, and clinical dental planning and management (Moorrees *et al.*, 1957; Bailit, 1975; O'Rourke and Crawford, 1980). There are several reasons why human teeth are suitable for such studies. Their physical strength resists decomposition changes, they carry with them a record of biological and environmental influences (Townsend, 1992a), they possess strong to moderate genetic determinants (Townsend, 1992b; Dempsey and Townsend, 2001), and their crown dimensions are fixed before tooth eruption, so they are not age-dependent (Berkovitz *et al.*, 2002).

Currently, little is known about odontometric variation within and between contemporary Malaysian populations. An appreciation of this normal variation is important in teaching and training dental students in local universities, for clinical orthodontic planning and treatment, and also for forensic identification and population studies of Malaysians.

Many studies have shown that tooth size varies within and between populations in several aspects: dimensional variability, the degree and pattern of sexual dimorphism, and asymmetry (Moorrees, 1951; Moorrees, 1957; Garn *et al.*, 1968a; Matis and Zwemer, 1971; Hanihara, 1976; Townsend and Brown, 1979; Kieser and Preston, 1981; Kieser *et al.*, 1985; Kieser, 1990; Yuen *et al.*, 1996; Yuen *et al.*, 1997; Hanihara and Ishida, 2005); the ratio of maxillary lateral incisor to central incisor (Tratman, 1950; Lasker and Lee, 1957; Potter *et al.*, 1981); and molar size sequence patterning (Harris and Nweeia, 1980; Axelsson and Kirveskari, 1983). However, up until now there has been a gap in knowledge about normal variation of tooth size in Malaysian populations.

The Malaysian population is heterogenous in that it comprises several major ethnic groups and a number of other minority groups. The largest group is the Malays who make up more than 50% of the total population. The other major groups are Chinese, Indians, Indigenous Borneons and Orang Asli. Indigenous Borneons live in Sabah and Sarawak, East Malaysia, while Orang Asli are only found on the Malaysian Peninsula. This study concentrates on odontometric variation of the major population groups living on the Malaysian Peninsula. The Orang Asli consists of three major tribes; Senoi, Proto-Malay and Negrito, and each major tribe can be further divided into six minor tribes. In this study, the Jahai, who are one of the minor

tribes of the Negrito, were chosen for study, mainly because they are small in number and reasonably isolated from other populations in Malaysia, but still accessible.

The origins of the Malaysian population can be described in two phases: prehistoric and modern. From the prehistoric phase, two models are useful to describe population migrations and origins. Jacob (1967) introduced the dual layer model which indicated that northern Mongoloid people migrated and invaded mainland Southeast Asia via South China. The invasion during the Neolithic period introduced new genetic material to the indigenous people who were believed to possess an Australomelanesoid appearance. The presence of indigenous people in the area received support from Von Koenigswald (1952), Bellwood (1978), and Matsumura and Majid (1999). Bellwood (1978) further commented that the Negritos, who are short, dark and dolichocephalic, had escaped from breeding with the northern Mongoloids. He postulated that small physical characteristics provided selective advantages for the Negritos to survive in isolated mountainous areas, and this saved them from interbreeding with the northern Mongoloids. This model also received support from Matsumura and Hudson (2005). The second model postulates that modern Southeast Asians originated from Late Pleistocene people who lived in Sundaland and who had undergone local evolutionary changes without genetic mixture. This model is supported by Turner (1987, 1990) and Hanihara (1992a, 1992b). Hanihara (1992a, 1992b) included in this model the hypothesized role of Proto-Malays who the author claimed as the indigenous direct lineage of the ancestral population in Sundaland. The Proto-Malays include the Negritos (Aeta of Luzon) and Dayak of Borneo who the author believed were the intermediate ancestors of modern Southeast Asians (Hanihara, 1992a).

The modern history of Malaysian populations includes a major influx of Chinese from South China and Indians from South India during 19th century (Zainuddin, 2003). These events have significantly contributed to the people we now see in modern Malaysia. The current situation introduces challenges to dental practitioners and to forensic scientists. In the first instance, normative data need to be established before predictive statistics for forensic purposes can be applied. This study aims to characterize normal odontometric variation within and between Malaysian populations and to assess the affinity between four major Malaysian ethnic groups.

4.2 Materials and methods

4.2.1 Abbreviations used in this study:

CV coefficient of variation

FDI Federation Dentaire Internationale

I1 central incisor; I2, lateral incisor; C, canine; P1, first premolar; P2, second premolar; M1, first molar; M2, second molar.

MD mesiodistal diameter; BL, buccolingual diameter

s standard deviation; $\bar{X}$, mean; n, sample size

UI1 upper central incisor; UI2, upper lateral incisor; UC, upper canine; UP1, upper first premolar; UP2, upper second premolar; UM1, upper first molar; UM2, upper second molar.

4.2.2 Sample

Dental models were collected from secondary schoolchildren and adults from public schools in Kelantan and Perak, and the Orang Asli new resettlement village in Perak. Alginate impressions and dental models were made according to manufacturer's instructions to avoid bias from impression materials and casting distortion. All oral examinations and impressions were undertaken in a mobile clinic vehicle, and diestone was poured immediately after rinsing the impressions under running tap water. All impressions were obtained using rigid steel trays.

Table 4.1 shows the age and sex distribution of subjects. Overall, young participants were selected so that interproximal wear would be minimal. There were approximately equal numbers of males and females in each ethnic group. For odontometric analyses, only 508 of the 790 sets of dental models were measured due to time constraints. The sample sizes in three groups; Malays, Chinese and Indians were considered sufficient for this study. The sample for the Jahai included all dental models collected during the field trip that satisfied the inclusion criteria, but the total number was relatively small. Accordingly, some variables with very small sample sizes were omitted from analysis.

Sample sizes needed to provide adequate statistical power were estimated using PS software version 1.0.17 (Dupont and Plummer, 1997). The calculations set the power of the study at 80% to detect statistically significant differences at an alpha level of 5%. The

calculations assumed a standard deviation of 0.5mm and equal sample sizes in the two groups (for independent t-tests). For paired t-tests, the sample size of the two groups is always equal. Appendices 4.1 and 4.2 show the range of sample sizes associated with various mean differences (in mm) between the two samples.

4.2.3 Inclusion criteria

All participants and parents of participants were asked to complete questionnaires seeking information about the participants' demography, ancestry and health. For underage (<18 years old) schoolchildren, written consent from parents was obtained before any procedures. Inclusion criteria were as follows: healthy, no craniofacial anomalies, no mixture of ancestry for three generations, and measurement landmarks not obscured by any restorations, caries, calculus, excessive tooth crown wear or casting defects.

4.2.4 Definitions of measurements

Mitutoyo digital calipers with modified beaks were used which enabled crown size measurements to be made to 0.01mm accuracy. The calipers were connected to a personal computer that enabled data to be transferred automatically to an Excel program (Microsoft Officeworks).

Measurements of mesiodistal diameters followed the definition of Moorrees (1957); that is, the maximum mesiodistal diameter of the dental crown was measured with the calipers held parallel with the labial/buccal and occlusal surfaces. For anterior teeth, the beaks were held parallel to the tooth axial axis. When a tooth was malposed or rotated, the measurement was taken between the points where it was assumed that normal contact should have occurred with the neighboring tooth. The buccolingual diameter was measured perpendicular to the mesiodistal plane and represented greatest distance between buccal/labial and lingual surfaces. (See Figures 3.3, 3.4, 3.5, and 3.6).

All right and left teeth, except third molars, were measured. Bilateralism was tested before deciding to use data from the right tooth only in inter-population comparisons. Replacement with the value for the left tooth was considered when the right tooth failed to comply with the inclusion criteria, e.g. was missing or distorted due to caries. This enabled sample sizes to be maximized.

4.2.5 Error study

The mesiodistal and buccolingual diameters were measured twice on different occasions for 60 subjects. The number of paired observations ranged from 29 to 59 for different teeth. The differences between the first and second recordings were analyzed by calculating the standard deviation of a single determination using the method of Dahlberg (1940), S_e,√ { Σ (d^2) / 2n} . The error variance, S_e^2, was calculated by squaring the Dahlberg statistic and expressing it as a percentage of the total observed variance: error variance (%) = (S_e^2/S_T^2)*100. According to (Houston, 1983), error variance should not exceed three percent of the total and if it exceeds 10 percent, the method of measurement needs to be reassessed. The coefficient of reliability can also be calculated as 1-(error variance (S_e^2)/total observed variance (S_T^2)).

Systematic error was assessed using paired t-tests. Significant results indicate a trend of intra-observer error in which there may be consistent differences (either larger or smaller) on the first or the second occasion.

4.2.6 Statistical analyses

Statistical analyses were applied with the use of SPSS (Statistical Packages for Social Science) computer program version 12.0.1 (SPSS Inc., 1989-2001) and Excel 2000 program (Microsoft Corporation 1983-2001).

4.2.6.1 Normality testing

Two tests, graphical plots (normal quantile plots) and statistical tests (modified Kolmogorov Smirnov and Shapiro Wilks) (Moore and McCabe, 2003), were used to assess normality of the data used in the asymmetry and inter-population studies. Normal quantile plots can also be used to assess extreme outlier(s) and they are useful for assessing normality when sample sizes are small (<30). With small sample sizes, statistical tests are less suitable. Therefore, both tests were used, as appropriate.

4.2.6.2 Outliers

Outlier cases were identified using standard scores (z-scores) calculated by subtracting each value from the corresponding sample mean and then dividing by the standard deviation. Cases with a z-score larger than four were checked for frank errors that may have occurred during measurement acquisition and/or data management. The formula of z-score is as follows:

$z = (X-\bar{X})/ SD$

X, individual measurement; $\bar{X}$, sample mean; SD, standard deviation

4.2.6.3 Descriptive statistics

Mean values ($\bar{X}$), standard deviations, (s or SD), sexual dimorphism rankings, and coefficients of variation (CV) were calculated.

4.2.6.3.1 Mean and standard deviation

The mean of n observations was calculated as:

$\bar{X} = 1/n \Sigma X_i$

The standard deviation, s, is the square root of the variance s^2:

$s= \{(1/(n-1) \Sigma (X_i - \bar{X})^2\}^{½}$

4.2.6.3.2 Sexual dimorphism ranking

The magnitude of sexual dimorphism for each variable was calculated using the formula provided by Garn *et al.* (1964):

$100*(\bar{X}$ males - $\bar{X}$ females)/$\bar{X}$ females.

4.2.6.3.3 Coefficients of variation

Coefficients of variation (CV) were used to quantify relative variability and enabled comparisons between different variables with different mean values.

The formula used to calculate CV was as follows:

$CV= (s/\bar{X})*100.$

Values for CV were compared between males and females using the Mann Whitney U-test.

4.2.6.4 Parametric tests

Student's t-tests were applied to compare the means between two samples. Two types of t-test were used in this study; depending on whether the samples were related or independent samples. For the independent t-tests, the variances of the two samples were first checked for homoscedasticity using a Levene test. SPSS program provided p-values of mean values comparison, for equal variances and unequal variances. If the test was significant, p-values were chosen for unequal variances.

4.2.6.4.1 Paired t-test

The paired t-test was used when comparing related samples. Normality tests were performed on the data obtained by subtracting data for the left side from the right between paired observations. If the sample size was 40 or more, the t-test is robust to non-normality but still sensitive to outliers (Moore and McCabe, 2003). Furthermore, according to the authors, if the sample is 15 or smaller, then t-tests should not be used if the data are non-normal or outliers are present. If sample sizes are at least 15, the t-test can be used, except in the case of outliers or strong skewness. The threshold for outliers was set at a z-score of 2.5 or more for sample sizes of 80 or less and 3-4 if larger sample were used (Hair *et al.*, 1995). The paired t-test was used to analyze systematic error and directional asymmetry.

The formula was as follows:

$t = x_{diff} / (s_{diff} / \sqrt{n})$ where

$s_{diff} = \sqrt{1/n-1(\Sigma d^2 - (\Sigma d^2)/n)}$

x_{diff}, mean difference; s_{diff}, standard deviation of the differences

4.2.6.4.2 Two sample t-test

The two sample t-tests compares means from two unrelated samples. This procedure is more robust than paired t-tests to non-normality and can be applied even if the sample size is small (as small as five) as long as both groups have equal sample sizes (Moore and McCabe, 2003). Homoscedasticity in both samples was tested using the Levene test. In SPSS calculations, options assuming equal variance or unequal variance are provided. If the Levene test probability was less than 5%, then unequal variance was assumed. This t-procedure was used to test sexual dimorphism.

The formula was as follows:

If equal variance assumed; $t=(x_1-x_2)/s_p \sqrt{1/n_1+1/n_2}$

where $s_p = \sqrt{(n_1-1)s_1^2 + (n_2-1)s_2^2}$

4.2.6.5 Non-parametric tests

These are distribution-free statistical tests. Two types were used in this study; chi-square and Fisher's exact test. There are several assumptions underlying the use of chi-square including independent observations, random sampling and expected cell counts not less than five. In any analysis with expected cell numbers less than five, Fisher's exact test is indicated (Howitt and Cramer, 2003). Fisher's exact test gives the probability for a one-tail distribution based on the proportion of factorials of total frequencies for each column and row divided by factorials of each frequency in observed cells and the sum total of columns and rows. In order to estimate probability for two tails, the probability derived should be divided by two.

In calculating chi-square:

If the observed cells contain frequencies of a,b,c and d

a	b	(a+b)
c	d	(c+d)
(a+c)	(b+d)	T= (a+b+c+d)

then chi-square= $T(ad-bc)^2/ \{(a+c)(b+d)(a+b)(c+d)\}$

However, if the expected cells contain values less than five, Fisher's exact Test should be applied:

Fisher's exact probability (2 tails)= $\{(a+c)!.(b+d)!.(a+b)!.(c+d)!\}/ \{(a!b!c!d!T!).(2)\}$

Another type of non-parametric statistics used was the Wilcoxon sign rank test for two related samples. This was applied in the asymmetry study for several variables in Jahai sample for whom assumptions relating to the paired t-test were violated.

4.2.6.6 Penrose shape distance coefficients

The sum of the relative size difference for all dependent variables between two samples may be calculated according to the formula provided by Penrose (1954). According to Penrose tooth shape has been shown to be useful in calculating phenetic distance. In addition, Corruccini (1973) supported the use of Penrose shape distance coefficients for taxonomic assessment. To control size differences between the sexes, standardized raw scores for mesiodistal and buccolingual measurements across ethnic groups for each variable were used in the phenetic distance assessment. Since four variables in the Jahai sample were omitted from this study, only 24 were used for phenetic assessment between the four Malaysian groups. Otherwise, for comparisons between the three groups, excluding the Jahai, all 28 variables were used. Penrose shape coefficients were used as input to generate graphical representations (dendrograms) of the results of the cluster analysis. An hierarchical clustering

procedure using Ward's method was applied and as the coefficients were in the same scales (all tooth size measurements were in millimeters), group similarity was calculated using squared Euclidean distance (Hair *et al.*, 1995). The formula for Penrose's shape distance coefficient was as follows:

$\sum_{m} (d^2)/m - \{\sum_{m} (d)\}^2/m^2$ where m, number of variables; d, difference in standardized measurements of two groups.

Table 4.1 Age and sex distribution of subjects

Ethnic group	Sex	N	Mean*	SD	Age range
Malays	Females	83	16.3	0.7	12-17
	Males	75	16.0	0.8	12-17
	Total	158	16.2	0.8	12-17
Chinese	Females	69	14.5	1.4	12-17
	Males	75	14.8	1.5	12-17
	Total	144	14.7	1.4	12-17
Indians	Females	78	15.9	1.5	13-18
	Males	73	15.7	1.3	13-18
	Total	151	15.8	1.4	13-18
Jahai	Females	29	27.9	8.6	17-51
	Males	26	26.5	10.8	13-51
	Total	55	27.2	9.6	13-51
Total	Females	259	17.0	5.0	12-51
	Males	249	16.6	5.0	12-51
	Total	508	16.8	5.0	12-51

N, sample size; SD, standard deviation; *, approximate age in years

Table 4.2 Systematic and experimental error in mesiodistal and buccolingual crown diameters

Tooth	N	mean difference	Se	Se^2	Var total	(%) error variance	t	Tooth	N	mean difference	Se	Se^2	Var total	(%) error variance	t
						Mesiodistal									
11	57	-0.008	0.05	0.002	0.273	0.7	-0.92	31	55	-0.011	0.04	0.002	0.141	1.1	-1.48
12	55	0.010	0.05	0.002	0.390	0.5	1.19	32	57	0.002	0.04	0.001	0.118	1.1	0.26
13	56	-0.003	0.05	0.002	0.267	0.9	-0.29	33	56	0.011	0.04	0.002	0.245	0.7	1.47
14	57	-0.010	0.05	0.002	0.188	1.2	-1.14	34	58	-0.004	0.04	0.002	0.154	1.3	-0.51
15	57	-0.004	0.05	0.002	0.226	1.1	-0.43	35	56	-0.008	0.05	0.002	0.166	1.3	-0.95
16	52	0.018	0.07	0.005	0.296	1.6	1.41	36	53	0.010	0.05	0.003	0.309	0.8	1.07
17	43	-0.010	0.06	0.004	0.252	1.4	-0.77	37	30	-0.004	0.04	0.002	0.411	0.4	-0.41
21	58	0.002	0.04	0.002	0.296	0.7	0.22	41	56	0.012	0.04	0.002	0.124	1.5	1.44
22	58	0.013	0.05	0.002	0.325	0.6	1.63	42	56	0.000	0.04	0.002	0.097	1.7	0.02
23	58	0.008	0.05	0.002	0.235	0.9	0.94	43	55	0.012	0.04	0.002	0.251	0.6	1.64
24	59	-0.005	0.04	0.002	0.188	1.0	-0.67	44	57	0.012	0.04	0.002	0.149	1.1	1.63
25	56	-0.007	0.05	0.002	0.228	0.9	-0.80	45	57	-0.009	0.04	0.002	0.206	1.0	-1.05
26	56	0.013	0.07	0.005	0.325	1.5	1.02	46	47	0.022	0.06	0.004	0.308	1.3	1.72
27	41	-0.011	0.06	0.004	0.293	1.2	-0.83	47	29	0.010	0.05	0.003	0.359	0.8	0.76

N, sample size; Se, single determination error (Dahlberg, 1940); Se^2, error variance; Var, variance; t, paired t-test; *, $p<0.05$; FDI notation

Table 4.2 (continued)

Tooth	N	mean difference	Se	Se^2	Var total	(%) error variance	t	Tooth	N	mean difference	Se	Se^2	Var total	(%) error variance	t
					Buccolingual										
11	47	0.004	0.04	0.002	0.260	0.7	0.45	31	50	0.009	0.04	0.002	0.182	1.0	1.13
12	46	-0.004	0.04	0.002	0.257	0.6	-0.51	32	50	0.008	0.06	0.003	0.173	1.8	0.69
13	46	-0.001	0.04	0.002	0.350	0.6	-0.11	33	45	0.010	0.05	0.002	0.331	0.7	0.98
14	54	-0.007	0.04	0.001	0.318	0.5	-0.93	34	55	0.007	0.05	0.002	0.251	0.9	0.85
15	52	0.005	0.04	0.002	0.380	0.4	0.72	35	50	-0.005	0.04	0.002	0.247	0.7	-0.56
16	54	0.000	0.04	0.002	0.378	0.4	0.00	36	56	0.001	0.04	0.002	0.295	0.6	0.09
17	49	-0.006	0.04	0.002	0.843	0.2	-0.64	37	53	0.008	0.04	0.002	0.405	0.4	0.99
21	51	0.010	0.04	0.001	0.226	0.6	1.33	41	40	0.012	0.04	0.001	0.184	0.7	1.46
22	49	0.011	0.04	0.001	0.229	0.6	1.42	42	43	0.019	0.05	0.002	0.168	1.4	1.81
23	50	0.011	0.04	0.002	0.392	0.4	1.40	43	46	0.004	0.05	0.002	0.352	0.7	0.42
24	56	0.001	0.04	0.002	0.309	0.6	0.16	44	56	-0.016	0.05	0.003	0.219	1.3	-1.61
25	57	0.003	0.04	0.001	0.382	0.4	0.42	45	50	0.009	0.04	0.002	0.243	0.8	0.99
26	57	-0.010	0.05	0.002	0.410	0.5	-1.15	46	53	-0.007	0.04	0.002	0.287	0.7	-0.77
27	49	-0.003	0.04	0.002	0.723	0.3	-0.32	47	49	-0.003	0.05	0.003	0.422	0.6	-0.29

4.3 Results

Appendix 4.1 indicates that, for mean differences larger than 0.2 mm with the power of the study set at 80%, alpha 5% and the standard deviation at 0.5 mm, the appropriate sample size for an independent t-test was estimated to be approximately 98 per group. For the paired t-test which is more sensitive than independent test (Appendices 4.2), a sample of approximately 50 per group was required.

Paired t-tests did not reveal any systematic differences between the two series of measurements in the replicability test, indicating that errors were small and unlikely to introduce any bias to the measurements. Measurement errors for tooth size variables, as indicated by the Dahlberg statistic, ranged in value from 0.04 to 0.07 mm (Table 4.2). Error variance was consistently less than 2% (reliability coefficient more than 0.98).

Normality tests showed that most of the data for tooth size measurements on the right side (left tooth was measured if the right tooth was excluded) were normally distributed (Appendices 4.3, 4.4, 4.5, 4.6). Kolmogorov-Smirnov and Shapiro-Wilk tests indicated that two variables in each of the Chinese and Indian samples significantly deviated from normal but none in Malays and Jahais. Overall, data generally conformed to a normal distribution.

All data were screened by calculating z-scores and none were associated with values larger than four. From normal quantile plots, several asymmetry variables in the Jahai sample showed obvious outliers and non-normal distribution. All sample sizes for the Jahai group (males and females separately) were less than 40, therefore, several asymmetry variables were assessed with the Wilcoxon Sign Rank test. Analyses for other groups proceeded with parametric tests.

Appendices 4.7 to 4.22 show basic descriptive statistics of tooth size measurements on the right and left side for Malays, Chinese, Indians and Jahai. These were the data used to assess directional asymmetry and to decide whether measurements on one side of the arch could be used to represent each ethnic group for inter-population analyses.

Tables 4.3 to 4.10 show the results of asymmetry analyses by sex for each ethnic group, analysed by paired t-tests and Wilcoxon sign rank tests. These tests indicated several examples of significant directional asymmetry in each ethnic group but the mean differences between antimeres for the significant variables were small. The largest differences were -0.12mm for the mesiodistal (MD) diameter of upper lateral incisor in female Jahai (Table 4.10) and 0.10mm for MD diameter of the upper second molar in female Malays (Table 4.4). The

smallest difference was -0.03mm for the MD diameter of lower lateral incisors in female Malays (Table 4.4) and the lower first molar in male Chinese (Table 4.5). No definite pattern in directional asymmetry was observed in tooth size in any of the ethnic groups, except for the buccolingual diameter of male and female Indians (Tables 4.7 and 4.8). Altogether, in 24 of 28 comparisons the right tooth was larger than the left tooth (positive sign) but for only 4 variables (from 24 variables) were these differences actually statistically significant at $p<0.05$.

Tables 4.11 to 4.14 show descriptive statistics, coefficients of variability and percentage sexual dimorphism values for every group. There was no sexual dimorphism in the pattern of relative variability (CV) except in Indians and Jahai (Figures 4.1, 4.3, 4.5 and 4.7). In Indians, CV values were higher in females for mesiodistal and buccolingual diameters (Figure 4.5) while in Jahai, values in males were larger than females in buccolingual diameters (Figure 4.7). The least variable teeth were the lower first molar in Malays (females) and Chinese (males) in both mesiodistal and buccolingual diameters, the mesiodistal diameter of the upper central incisor and buccolingual of the upper first molar in Indian males, and the upper second premolar in mesiodistal diameter for Jahai males and the upper first molar in buccolingual diameter for Jahai females. The most variable teeth were the mesiodistal diameter of the upper lateral incisor in Malay, Chinese, Indian and Jahai females, whereas for buccolingual diameters the most variable teeth were the lower canine in Malay and Chinese males and the upper lateral incisor in Indian females and Jahai males. The ranking of variability within morphological tooth classes suggested only Chinese complied with the pattern of variability LI1>LI2, LP2>LP1, LM2>LM1 as proposed by Dahlberg (1945). The other three ethnic groups did not follow exactly this pattern, especially for lower incisors, and upper and lower premolars.

The amount of sexual dimorphism was found to be largest in the Chinese. The range of values was from 1.7 to 6.7. Indians showed the least sexual dimorphism with values ranging from 1.2 to 4.5. The lower canine was identified as the most dimorphic tooth in all four groups. Other highly dimorphic teeth were: the upper canine in both dimensions for Malays; the mesiodistal diameter of the lower second molar, the buccolingual diameter of the lower first premolar in Chinese; the buccolingual diameter of the lower second premolar in Indians; and the upper first molar in Jahai. There was no single tooth that was the least dimorphic tooth in each of the four ethnic groups. Comparisons of the magnitude of sexual dimorphism between the four ethnic groups for both buccolingual and mesiodistal diameters indicated that buccolingual dimensions tended to be more dimorphic. Approximately 75% of the 28 tooth size variables in Malays, Chinese and Indians were statistically significantly larger in males than females. The Chinese showed the most sexually dimorphic variables. None of the ethnic

groups provided support for the canine sex dimorphism theory (Garn *et al.*, 1967b; Harris and Bailit, 1988). There were no clear trends in the amount of sexual dimorphism between maxillary and mandibular teeth for Jahai, whereas in Chinese, the mandibular teeth were more dimorphic than those in the maxilla in mesiodistal and buccolingual diameters. The Malays did not show clear trends in sex dimorphism between maxillary and mandibular teeth for buccolingual dimensions whereas in Indians, no sex dimorphism was shown in the mesiodistal diameter. For Malays, mandibular teeth were more dimorphic in mesiodistal diameters while, in Indians, the maxillary teeth were more dimorphic in buccolingual diameters.

Average dimorphism percentage values are shown in Table 4.15. The range of dimorphism in the Malaysian samples fell within the range reported for other modern human populations. The Chinese sample showed the highest sexual dimorphism while the Jahai sample showed the least. On average, sexual dimorphism in buccolingual diameters was found to be greater than in mesiodistal dimensions.

Table 4.16 shows the ratios of the average values of the mesiodistal diameters of upper lateral incisors to upper central incisors among several ethnic groups. The ratios in all Malaysian samples fell close to those for other Mongoloid groups.

Table 4.17 shows molar size sequences for maxillary and mandibular teeth of Malaysians and several other ethnic groups. The M1>M2 pattern dominated in all groups. The frequency of M1>M2 in Malaysians was found to be higher in the mandible than in the maxilla. There was no evidence of sexual dimorphism in the frequencies of M2>M1 and M1>M2 in either the maxilla or mandible. The pattern of molar size sequence showed some variation between the ethnic groups. The order of variation for M1>M2, from high to low frequencies (percentages) in males and females was as follows: Malays>Jahai>Chinese>Indians. Generally Malaysians showed a higher frequency of cases with M1>M2 than has been reported for Australian Aborigines, American Whites and Blacks (Townsend and Brown, 1983).

Table 4.18 shows population affinities within the Malaysian ethnic groups based on Penrose shape distance analyses. The dendrograms derived from cluster analyses using 28 variables for comparisons between three groups, indicated two clusters. The first cluster comprised Malays and Chinese, with Indians in the second cluster (Table 4.18 and Figure 4.9). Utilizing 24 variables, the dendrogram to display the relationships between all four ethnic groups (Table 4.19 and Figure 4.10) showed there were two major clusters. Three ethnic groups formed the first major cluster, with the Indians being subdivided from the Malays and Chinese, while the Jahai formed the second major cluster.

Table 4.3 Directional asymmetry for male Malays

Tooth pair	n	Xd	SD	95% CI		*t*		Tooth pair	n	Xd	SD	95% CI		*t*	
				Maxilla								Mandible			
Mesiodistal								Mesiodistal							
I1	71	-0.01	0.14	-0.05	0.02	-0.850		I1	70	0.00	0.20	-0.05	0.04	-0.135	
I2	69	-0.01	0.20	-0.06	0.04	-0.422		I2	69	-0.02	0.15	-0.05	0.02	-0.883	
C	68	0.04	0.21	-0.01	0.09	1.702		C	72	-0.06	0.17	-0.10	-0.02	-2.839	*
P1	65	-0.04	0.16	-0.08	0.00	-1.917		P1	74	0.01	0.16	-0.03	0.05	0.508	
P2	62	0.03	0.21	-0.03	0.08	0.932		P2	62	-0.01	0.23	-0.07	0.05	-0.366	
M1	55	0.00	0.09	-0.03	0.02	-0.409		M1	61	-0.05	0.13	-0.09	-0.02	-3.090	**
M2	50	0.08	0.32	-0.01	0.17	1.829		M2	36	-0.09	0.31	-0.19	0.02	-1.665	
Buccolingual								Buccolingual							
I1	59	0.03	0.16	-0.01	0.07	1.475		I1	49	0.03	0.15	-0.01	0.07	1.342	
I2	58	0.05	0.33	-0.03	0.14	1.206		I2	53	0.04	0.21	-0.01	0.10	1.508	
C	61	-0.04	0.26	-0.10	0.03	-1.158		C	53	-0.03	0.24	-0.09	0.04	-0.765	
P1	67	0.05	0.16	0.01	0.09	2.702	*	P1	66	0.06	0.21	0.01	0.11	2.285	*
P2	66	0.07	0.19	0.03	0.12	3.196	**	P2	47	0.02	0.16	-0.02	0.07	1.082	
M1	62	-0.05	0.22	-0.10	0.01	-1.654		M1	53	0.04	0.18	-0.01	0.08	1.453	
M2	54	-0.01	0.27	-0.08	0.07	-0.147		M2	60	0.08	0.24	0.02	0.14	2.647	*

Xd, mean differences; n, number of sample; SD, standard deviation; t, paired t-test; df, degrees of freedom; CI, confidence interval of the difference; *, significant at $p<0.05$; **, significant at $p<0.01$

Table 4.4 Directional asymmetry for female Malays

Tooth pair	n	Xd	SD	95% CI		t		Tooth pair	n	Xd	SD	95% CI		t	
				Maxilla								Mandible			
Mesiodistal								Mesiodistal							
I1	77	0.00	0.18	-0.05	0.04	-0.231		I1	75	0.01	0.16	-0.03	0.05	0.597	
I2	74	0.03	0.31	-0.04	0.10	0.783		I2	79	-0.03	0.13	-0.06	0.00	-2.105	*
C	73	-0.01	0.16	-0.05	0.02	-0.748		C	77	-0.02	0.18	-0.06	0.02	-0.892	
P1	80	0.00	0.17	-0.04	0.04	0.086		P1	78	-0.03	0.19	-0.08	0.01	-1.486	
P2	74	0.02	0.24	-0.04	0.07	0.544		P2	63	-0.03	0.17	-0.07	0.01	-1.322	
M1	64	-0.01	0.12	-0.04	0.01	-0.968		M1	66	-0.02	0.10	-0.04	0.01	-1.396	
M2	42	0.10	0.22	0.03	0.17	2.860	*	M2	28	0.01	0.30	-0.11	0.12	0.108	
Buccolingual								Buccolingual							
I1	71	0.04	0.19	0.00	0.08	1.848		I1	56	0.01	0.16	-0.04	0.05	0.340	
I2	68	0.01	0.24	-0.05	0.07	0.309		I2	64	0.06	0.16	0.02	0.10	2.764	*
C	66	-0.02	0.23	-0.08	0.04	-0.710		C	63	-0.02	0.26	-0.08	0.05	-0.500	
P1	75	0.06	0.19	0.02	0.10	2.797	*	P1	67	0.04	0.21	-0.01	0.09	1.534	
P2	78	0.03	0.21	-0.02	0.08	1.224		P2	56	-0.01	0.23	-0.07	0.05	-0.356	
M1	71	-0.01	0.21	-0.06	0.04	-0.377		M1	63	0.01	0.17	-0.03	0.05	0.552	
M2	60	-0.04	0.29	-0.12	0.03	-1.168		M2	61	-0.05	0.23	-0.11	0.01	-1.794	

Xd, mean differences; n, sample number; SD, standard deviation; t, paired t-test; df, degrees of freedom; CI, confidence interval of the difference; *, significant at $p<0.05$; **, significant at $p<0.01$

Table 4.5 Directional asymmetry for male Chinese

Tooth pair	n	Xd	SD	95% CI		t		Tooth pair	n	Xd	SD	95% CI		t	
				Maxilla								Mandible			
Mesiodistal								Mesiodistal							
I1	66	0.00	0.15	-0.03	0.04	0.202		I1	65	-0.03	0.14	-0.06	0.01	-1.579	
I2	64	-0.03	0.25	-0.09	0.04	-0.797		I2	66	-0.04	0.14	-0.08	-0.01	-2.484	*
C	60	0.05	0.19	0.00	0.10	2.041		C	64	-0.03	0.18	-0.07	0.01	-1.350	
P1	63	-0.03	0.17	-0.08	0.01	-1.605		P1	65	0.06	0.18	0.01	0.10	2.568	*
P2	59	0.01	0.18	-0.04	0.06	0.431		P2	48	-0.02	0.22	-0.08	0.04	-0.656	
M1	53	0.02	0.10	-0.01	0.04	1.158		M1	59	-0.03	0.09	-0.06	-0.01	-2.648	*
M2	41	0.02	0.23	-0.06	0.09	0.430		M2	14	0.08	0.38	-0.14	0.30	0.813	
Buccolingual								Buccolingual							
I1	52	0.01	0.16	-0.04	0.05	0.355		I1	50	0.03	0.15	-0.02	0.07	1.164	
I2	44	0.00	0.23	-0.07	0.07	-0.045		I2	52	-0.01	0.21	-0.07	0.05	-0.268	
C	46	0.03	0.20	-0.03	0.09	0.962		C	47	0.00	0.23	-0.07	0.07	0.094	
P1	63	0.04	0.19	-0.01	0.08	1.548		P1	63	0.03	0.22	-0.03	0.09	1.095	
P2	63	-0.02	0.25	-0.08	0.05	-0.536		P2	54	0.01	0.20	-0.04	0.07	0.455	
M1	61	-0.04	0.18	-0.09	0.01	-1.641		M1	58	0.05	0.15	0.01	0.09	2.722	*
M2	41	-0.04	0.22	-0.11	0.03	-1.190		M2	44	-0.06	0.30	-0.15	0.03	-1.359	

Xd, mean differences; n, sample number; SD, standard deviation; t, paired t-test; df, degrees of freedom; CI, confidence interval of the difference; *, significant at $p<0.05$; **, significant at $p<0.01$

Table 4.6 Directional asymmetry for female Chinese

Tooth pair	n	Xd	SD	95% CI		t		Tooth pair	n	Xd	SD	95% CI		t	
Mesiodistal								Mesiodistal							
I1	60	-0.01	0.16	-0.05	0.031	-0.520		I1	56	0.01	0.15	-0.04	0.047	0.287	
I2	57	0.01	0.20	-0.04	0.064	0.349		I2	60	-0.02	0.13	-0.05	0.011	-1.318	
C	58	0.02	0.17	-0.03	0.065	0.859		C	62	0.00	0.18	-0.05	0.047	0.021	
P1	59	0.01	0.17	-0.03	0.058	0.548		P1	61	0.05	0.17	0.00	0.089	2.179	*
P2	59	-0.01	0.20	-0.06	0.043	-0.324		P2	51	-0.02	0.17	-0.07	0.028	-0.857	
M1	51	0.00	0.08	-0.02	0.022	0.018		M1	55	-0.03	0.13	-0.06	0.009	-1.487	
M2	33	-0.07	0.29	-0.17	0.031	-1.413		M2	20	-0.09	0.35	-0.26	0.072	-1.176	
Buccolingual								Buccolingual							
I1	53	-0.06	0.19	-0.11	-0.004	-2.155	*	I1	49	-0.04	0.18	-0.09	0.015	-1.417	
I2	49	-0.04	0.26	-0.11	0.040	-0.939		I2	51	0.00	0.19	-0.05	0.058	0.176	
C	48	0.02	0.25	-0.05	0.090	0.481		C	48	0.03	0.23	-0.04	0.093	0.770	
P1	59	0.00	0.27	-0.07	0.068	-0.049		P1	59	0.04	0.26	-0.02	0.112	1.287	
P2	59	-0.01	0.24	-0.07	0.048	-0.430		P2	51	0.01	0.21	-0.05	0.073	0.439	
M1	56	-0.04	0.16	-0.08	0.006	-1.708		M1	60	0.06	0.15	0.03	0.100	3.344	**
M2	42	-0.02	0.30	-0.11	0.078	-0.340		M2	38	0.01	0.27	-0.08	0.097	0.213	

Xd, mean differences; n, sample number; SD, standard deviation; t, paired t-test; df, degrees of freedom; CI, confidence interval of the difference; *, significant at $p<0.05$; **, significant at $p<0.01$

Table 4.7 Directional asymmetry for male Indians

Tooth pair	n	Xd	SD	95% CI		t		Tooth pair	n	Xd	SD	95% CI		t	
				Maxilla								Mandible			
Mesiodistal								Mesiodistal							
I1	63	0.01	0.14	-0.03	0.04	0.431		I1	69	0.00	0.16	-0.04	0.04	0.016	
I2	67	-0.06	0.29	-0.13	0.01	-1.743		I2	64	-0.01	0.14	-0.04	0.03	-0.438	
C	61	0.05	0.17	0.01	0.09	2.286	*	C	67	0.00	0.14	-0.03	0.03	-0.063	
P1	61	-0.01	0.14	-0.05	0.03	-0.499		P1	66	0.01	0.18	-0.04	0.05	0.245	
P2	64	0.03	0.23	-0.03	0.09	1.014		P2	58	0.00	0.20	-0.05	0.05	0.060	
M1	62	-0.01	0.08	-0.03	0.01	-1.217		M1	58	-0.01	0.15	-0.05	0.03	-0.621	
M2	34	0.03	0.29	-0.07	0.13	0.588		M2	21	-0.05	0.29	-0.18	0.09	-0.744	
Buccolingual								Buccolingual							
I1	60	0.03	0.21	-0.02	0.08	1.082		I1	53	-0.02	0.14	-0.06	0.02	-0.837	
I2	58	0.02	0.30	-0.06	0.10	0.563		I2	55	0.09	0.22	0.03	0.15	3.030	**
C	51	0.01	0.18	-0.04	0.07	0.545		C	38	0.04	0.23	-0.04	0.12	1.063	
P1	67	0.04	0.18	0.00	0.08	1.835		P1	65	0.07	0.26	0.01	0.14	2.179	*
P2	59	0.05	0.24	-0.01	0.11	1.613		P2	65	0.00	0.22	-0.05	0.06	0.120	
M1	66	-0.01	0.19	-0.06	0.03	-0.641		M1	62	0.02	0.18	-0.03	0.07	0.908	
M2	58	0.00	0.32	-0.08	0.09	0.057		M2	54	0.02	0.22	-0.04	0.08	0.600	

Xd, mean differences; n, sample number; SD, standard deviation; t, paired t-test; df, degrees of freedom; CI, confidence interval of the difference; *, significant at $p<0.05$; **, significant at $p<0.01$

Table 4.8 Directional asymmetry for female Indians

Tooth pair		Xd	SD	95% CI		t		Tooth pair		Xd	SD	95% CI		t	
				Maxilla								Mandible			
Mesiodistal								Mesiodistal							
I1	71	-0.03	0.14	-0.06	0.01	-1.504		I1	73	0.00	0.14	-0.03	0.03	0.111	
I2	69	0.02	0.26	-0.04	0.08	0.635		I2	75	0.01	0.13	-0.02	0.04	0.815	
C	70	0.02	0.16	-0.01	0.06	1.290		C	70	0.01	0.14	-0.03	0.04	0.421	
P1	73	-0.01	0.15	-0.04	0.03	-0.404		P1	72	-0.04	0.14	-0.07	-0.01	-2.362	*
P2	60	0.02	0.18	-0.03	0.06	0.726		P2	59	-0.01	0.19	-0.06	0.04	-0.480	
M1	61	0.01	0.13	-0.02	0.05	0.841		M1	65	-0.04	0.14	-0.07	0.00	-2.064	*
M2	45	0.03	0.29	-0.06	0.11	0.611		M2	23	0.00	0.17	-0.07	0.07	-0.012	
Buccolingual								Buccolingual							
I1	64	-0.03	0.21	-0.08	0.02	-1.158		I1	61	0.00	0.18	-0.05	0.04	-0.071	
I2	59	-0.04	0.24	-0.10	0.02	-1.356		I2	61	0.04	0.16	0.00	0.08	1.796	
C	61	0.06	0.24	0.00	0.12	1.902		C	47	0.05	0.20	0.00	0.11	1.851	
P1	71	0.09	0.19	0.04	0.13	3.726	**	P1	65	0.07	0.22	0.01	0.12	2.458	*
P2	65	0.02	0.19	-0.03	0.06	0.670		P2	67	0.02	0.20	-0.03	0.07	0.766	
M1	72	0.02	0.16	-0.02	0.05	0.835		M1	68	0.00	0.16	-0.03	0.04	0.195	
M2	63	0.01	0.28	-0.06	0.09	0.403		M2	53	0.02	0.22	-0.04	0.08	0.677	

Xd, mean differences; n, sample number; SD, standard deviation; t, paired t-test; df, degrees of freedom; CI, confidence interval of the difference; *, significant at $p<0.05$; **, significant at $p<0.01$

Table 4.9 Directional asymmetry for male Jahai

Tooth pair	n	Xd	SD	95% CI		t	W	Tooth pair	n	Xd	SD	95% CI		t	W
				Maxilla								Mandible			
Mesiodistal								Mesiodistal							
I1	20	-0.01	0.13	-0.08	0.05	-0.484		I1	20	-0.03	0.18	-0.11	0.06	-0.640	
I2	19	0.09	0.23	-0.03	0.20	1.595	-1.368	I2	22	-0.05	0.24	-0.16	0.05	-1.076	
C	20	0.03	0.15	-0.04	0.10	0.830		C	17	-0.07	0.20	-0.17	0.03	-1.442	
P1	20	-0.03	0.16	-0.10	0.04	-0.803		P1	17	-0.04	0.20	-0.14	0.06	-0.824	
P2	15	-0.06	0.35	-0.25	0.14	-0.623		P2	19	-0.08	0.27	-0.21	0.06	-1.209	
M1	16	-0.04	0.17	-0.13	0.05	-0.917	-0.155	M1	14	-0.08	0.11	-0.14	-0.02	-2.731	
M2	16	0.04	0.41	-0.18	0.25	0.370		M2	15	-0.09	0.32	-0.27	0.08	-1.134	-1.852
Buccolingual								Buccolingual							
I1	10	-0.07	0.14	-0.17	0.03	-1.517									
I2	9	0.09	0.41	-0.22	0.41	0.689									
C															
P1	12	-0.06	0.23	-0.21	0.08	-0.952		P1	11	0.13	0.13	0.05	0.22	3.376	
P2	13	0.03	0.32	-0.16	0.23	0.376	-0.105	P2	10	0.00	0.20	-0.14	0.15	0.047	
M1	8	-0.02	0.24	-0.22	0.19	-0.203	-0.771	M1	9	0.02	0.10	-0.05	0.10	0.732	
M2	9	0.04	0.29	-0.18	0.26	0.410	-0.296	M2	10	0.14	0.14	0.04	0.23	3.172	

Xd, mean differences; n, sample number; SD, standard deviation; t, paired t-test; df, degrees of freedom; CI, confidence interval of the difference; *, significant at $p<0.05$; **, significant at $p<0.01$

Table 4.10 Directional asymmetry for female Jahai

Tooth pair	n	Xd	SD	95% CI		t		W		Tooth pair	n	Xd	SD	95% CI		t		W	
				Maxilla										Mandible					
Mesiodistal										Mesiodistal									
I1	19	0.00	0.21	-0.10	0.10	0.000				I1	23	0.04	0.15	-0.02	0.10	1.275			
I2	20	-0.12	0.17	-0.20	-0.04	-3.032	*	-2.996	*	I2	27	-0.05	0.12	-0.09	0.00	-2.060			
C	23	-0.06	0.12	-0.11	0.00	-2.220	*			C	25	-0.01	0.14	-0.07	0.05	-0.300			
P1	26	-0.05	0.20	-0.13	0.03	-1.287				P1	27	-0.05	0.18	-0.12	0.03	-1.323			
P2	22	0.00	0.21	-0.09	0.09	0.041				P2	20	0.05	0.24	-0.06	0.16	0.954			
M1	17	-0.01	0.13	-0.07	0.06	-0.206		-0.095		M1	12	-0.04	0.15	-0.14	0.05	-0.971		-1.513	
M2	15	0.19	0.35	0.00	0.38	2.121		-1.875		M2	20	-0.01	0.27	-0.14	0.12	-0.181			
Buccolingual										Buccolingual									
I1	16	0.05	0.17	-0.05	0.14	1.047													
I2	16	-0.05	0.25	-0.18	0.09	-0.738													
C	19	0.02	0.20	-0.08	0.11	0.338		-0.196											
P1	19	0.01	0.18	-0.07	0.10	0.340				P1	16	-0.05	0.25	-0.18	0.09	-0.751			
P2	19	0.01	0.23	-0.11	0.12	0.100				P2	11	0.02	0.19	-0.11	0.14	0.293			
M1	11	-0.07	0.25	-0.24	0.10	-0.892				M1	8	-0.05	0.16	-0.18	0.09	-0.856			
M2	12	-0.05	0.28	-0.23	0.12	-0.640				M2	10	-0.11	0.28	-0.32	0.09	-1.248			

Xd, mean differences; n, sample number; SD, standard deviation; t, paired t-test; df, degrees of freedom; W, value of Z for Wilcoxon Sign Rank Test; CI, confidence interval of the difference; *, significant at $p<0.05$; **, significant at $p<0.01$

Table 4.11 Basic descriptive statistics and sexual dimorphism for permanent tooth size in Malays

Tooth	Females				Males					Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Maxilla													
Mesiodistal															
I1	79	8.50	0.56	6.6	73	8.70	*	0.46	5.3	152	8.59	0.52	6.1	NS	2.4
I2	80	7.00	0.65	9.3	73	7.08		0.58	8.2	153	7.04	0.62	8.8	NS	1.2
C	81	7.81	0.49	6.2	72	8.27	**	0.43	5.2	153	8.03	0.51	6.4	NS	5.9
P1	83	7.44	0.41	5.5	73	7.52		0.42	5.6	156	7.48	0.42	5.6	NS	1.2
P2	83	6.99	0.43	6.2	73	7.03		0.43	6.1	156	7.01	0.43	6.1	NS	0.6
M1	77	10.53	0.49	4.7	72	10.69		0.52	4.8	149	10.61	0.51	4.8	NS	1.4
M2	70	9.90	0.59	6.0	67	10.16	**	0.48	4.7	137	10.03	0.55	5.5	S	2.7

Table 4.11 (continued)

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Maxilla													
Buccolingual															
I1	80	7.13	0.48	6.7	69	7.41	**	0.49	6.6	149	7.26	0.50	6.9	NS	4.0
I2	77	6.45	0.45	7.0	70	6.75	**	0.47	6.9	147	6.59	0.48	7.3	NS	4.7
C	78	7.92	0.52	6.6	69	8.29	**	0.53	6.4	147	8.10	0.56	6.9	NS	4.7
P1	81	9.49	0.46	4.9	73	9.77	**	0.50	5.1	154	9.62	0.50	5.2	NS	3.0
P2	81	9.40	0.54	5.7	72	9.60	*	0.54	5.6	153	9.49	0.55	5.8	NS	2.1
M1	79	11.18	0.49	4.4	69	11.61	**	0.57	4.9	148	11.38	0.57	5.0	NS	3.9
M2	76	11.05	0.62	5.6	72	11.41	**	0.70	6.2	148	11.23	0.68	6.1	NS	3.3

Table 4.11 (continued)

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Mandible													
Mesiodistal															
I1	81	5.44	0.32	5.9	71	5.56	*	0.37	6.6	152	5.49	0.35	6.3	NS	2.3
I2	81	6.06	0.38	6.3	73	6.14		0.34	5.6	154	6.10	0.36	6.0	NS	1.2
C	80	6.77	0.39	5.8	73	7.21	**	0.41	5.6	153	6.98	0.45	6.5	NS	6.5
P1	80	7.28	0.42	5.8	75	7.43	*	0.45	6.1	155	7.36	0.44	6.0	NS	2.1
P2	79	7.32	0.45	6.2	72	7.39		0.46	6.3	151	7.35	0.46	6.2	NS	1.0
M1	78	11.35	0.47	4.1	72	11.66	**	0.50	4.3	150	11.50	0.50	4.4	NS	2.7
M2	56	10.28	0.64	6.3	60	10.59	*	0.66	6.2	116	10.44	0.67	6.4	NS	3.0

Table 4.11 (continued)

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Mandible													
Buccolingual															
I1	68	5.76	0.38	6.6	60	5.97	**	0.37	6.2	128	5.86	0.39	6.6	NS	3.7
I2	70	6.14	0.38	6.1	67	6.30	*	0.47	7.4	137	6.22	0.43	6.9	NS	2.7
C	73	7.12	0.48	6.8	67	7.52	**	0.59	7.8	140	7.31	0.57	7.8	S	5.6
P1	75	7.99	0.44	5.5	73	8.28	**	0.52	6.3	148	8.14	0.50	6.2	NS	3.7
P2	70	8.55	0.47	5.5	68	8.81	**	0.41	4.7	138	8.68	0.46	5.3	NS	3.0
M1	76	10.81	0.46	4.3	72	10.99	*	0.50	4.5	148	10.90	0.49	4.5	NS	1.6
M2	72	10.44	0.46	4.4	70	10.84	**	0.58	5.4	142	10.64	0.56	5.2	NS	3.7

N, sample size; SD, standard deviation; CV, coefficient of variation (% SD/mean); % sex dimorphism; (mean male-mean female/mean female)100; S, equal variances not assumed; NS; equal variances assumed; *, $p<0.05$; **, $p<0.01$

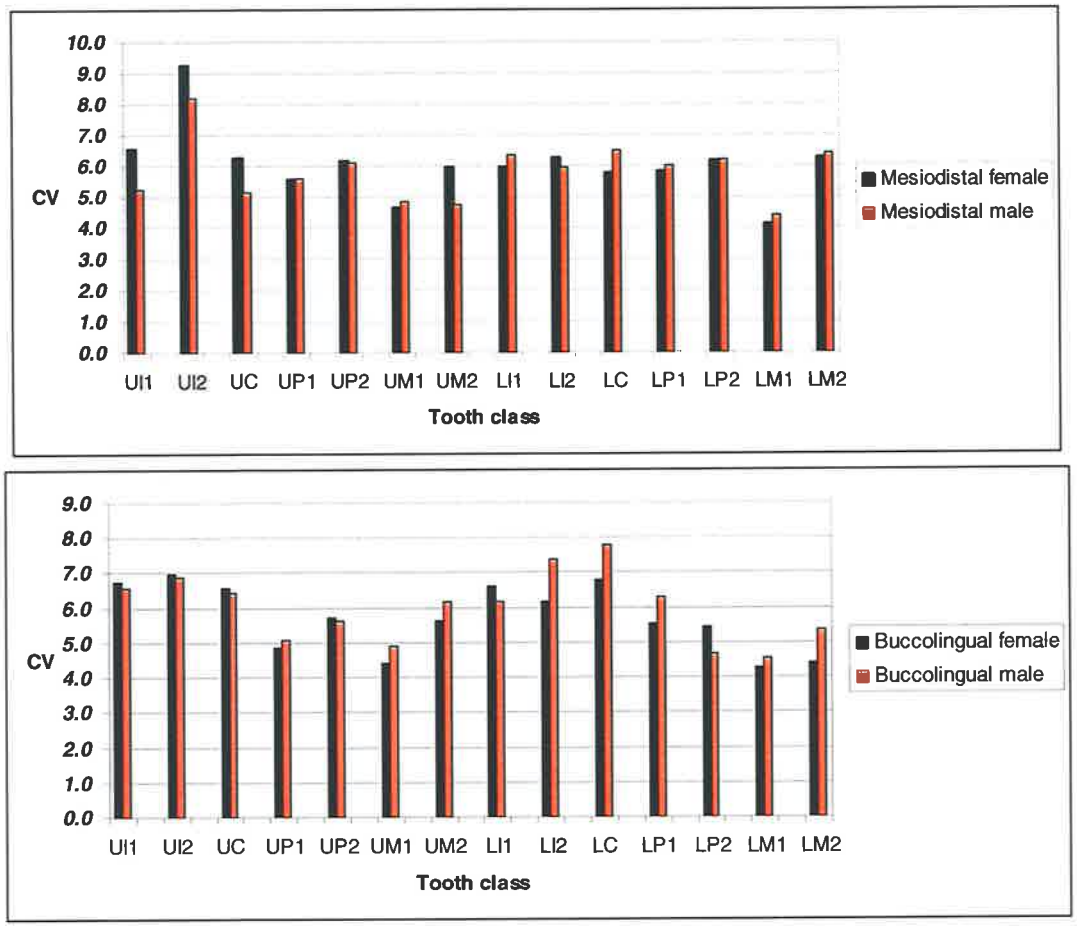


Figure 4.1 Relative variability in tooth size of Malays

*, $p<0.05$

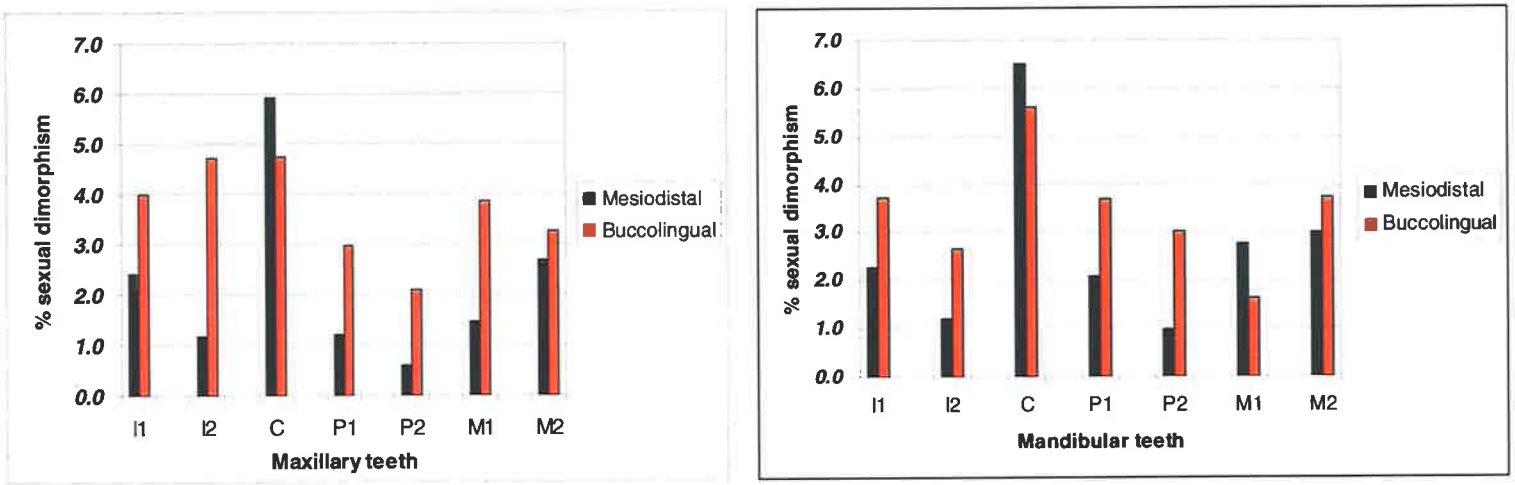


Figure 4.2 Sexual dimorphism in tooth size of Malays

Table 4.12 Basic descriptive statistics and sexual dimorphism for permanent tooth size in Chinese

Tooth	Females				Males					Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Maxilla													
Mesiodistal															
I1	68	8.60	0.46	5.4	74	8.91	**	0.48	5.4	142	8.76	0.49	5.6	NS	3.6
I2	67	7.09	0.56	8.0	71	7.39	**	0.57	7.7	138	7.25	0.58	8.1	NS	4.3
C	66	8.07	0.43	5.3	74	8.38	**	0.48	5.8	140	8.23	0.48	5.9	NS	3.9
P1	68	7.52	0.42	5.6	73	7.76	**	0.41	5.3	141	7.64	0.43	5.6	NS	3.2
P2	66	7.06	0.41	5.8	71	7.30	**	0.44	6.1	137	7.18	0.44	6.2	NS	3.5
M1	68	10.37	0.51	4.9	70	10.67	**	0.47	4.4	138	10.52	0.51	4.9	NS	2.8
M2	53	9.91	0.59	5.9	56	10.30	**	0.51	4.9	109	10.11	0.58	5.7	NS	4.0

Table 4.12 (continued)

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Maxilla													
Buccolingual															
I1	66	7.09	0.40	5.7	66	7.41	**	0.49	6.6	132	7.25	0.47	6.5	NS	4.4
I2	62	6.55	0.51	7.8	65	6.79	**	0.51	7.5	127	6.67	0.52	7.8	NS	3.7
C	63	8.11	0.49	6.1	65	8.35	*	0.58	6.9	128	8.23	0.55	6.6	NS	2.9
P1	66	9.57	0.47	4.9	72	10.02	**	0.54	5.4	138	9.80	0.55	5.6	NS	4.6
P2	67	9.32	0.56	6.1	72	9.76	**	0.62	6.4	139	9.55	0.63	6.6	NS	4.7
M1	67	11.19	0.50	4.5	73	11.74	**	0.51	4.3	140	11.48	0.57	5.0	NS	4.9
M2	56	11.05	0.60	5.4	62	11.58	**	0.78	6.7	118	11.33	0.74	6.6	S	4.8

Table 4.12 (continued)

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Mandible													
Mesiodistal															
I1	65	5.48	0.33	6.0	74	5.60	*	0.32	5.8	139	5.54	0.33	6.0	NS	2.2
I2	67	6.07	0.31	5.1	74	6.18		0.35	5.7	141	6.13	0.34	5.5	NS	1.8
C	68	6.90	0.38	5.6	74	7.29	**	0.41	5.6	142	7.10	0.44	6.2	NS	5.7
P1	68	7.33	0.38	5.1	72	7.58	**	0.37	4.9	140	7.46	0.39	5.3	NS	3.4
P2	64	7.26	0.45	6.2	72	7.58	**	0.43	5.7	136	7.43	0.47	6.3	NS	4.4
M1	68	11.21	0.51	4.6	72	11.64	**	0.42	3.6	140	11.43	0.52	4.5	NS	3.9
M2	43	10.13	0.54	5.3	45	10.81	**	0.64	5.9	88	10.48	0.68	6.5	NS	6.7

Table 4.12 (continued)

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Mandible													
Buccolingual															
I1	62	5.75	0.35	6.1	59	6.00	**	0.36	5.9	121	5.87	0.37	6.4	NS	4.3
I2	61	6.18	0.35	5.7	64	6.28		0.34	5.4	125	6.23	0.35	5.6	NS	1.7
C	64	7.23	0.49	6.7	69	7.47	**	0.61	8.1	133	7.36	0.56	7.6	S	3.3
P1	66	8.06	0.36	4.5	70	8.47	**	0.49	5.8	136	8.27	0.47	5.7	S	5.0
P2	60	8.59	0.40	4.7	71	8.92	**	0.56	6.2	131	8.77	0.52	5.9	S	3.8
M1	68	10.75	0.44	4.1	71	11.13	**	0.44	4.0	139	10.94	0.48	4.4	NS	3.5
M2	60	10.41	0.50	4.8	63	10.85	**	0.50	4.6	123	10.63	0.54	5.1	NS	4.2

N, sample size; SD, standard deviation; CV, coefficient of variation (100*SD/mean); % sex dimorphism (100*mean male-mean female/mean female); S, variance was not equally assumed; NS, equal variance assumed; *, $p<0.05$; **, $p<0.01$

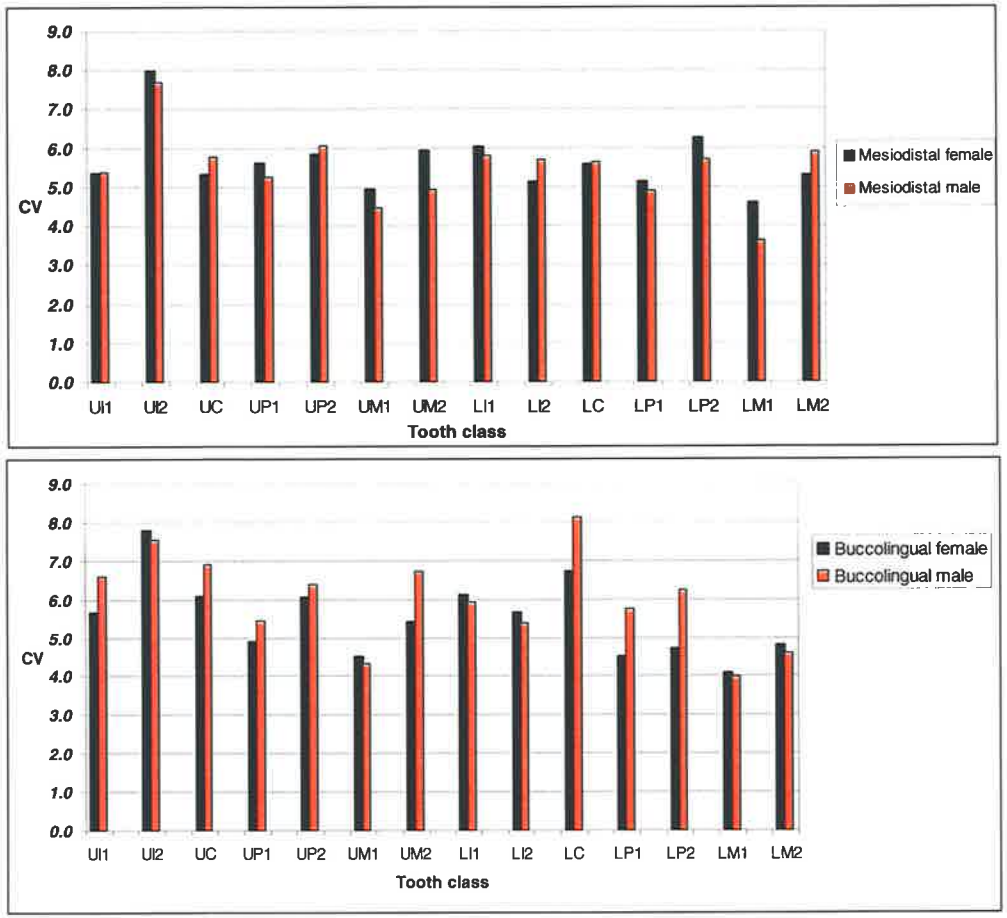


Figure 4.3 Relative variability in tooth size of Chinese

*, $p<0.05$

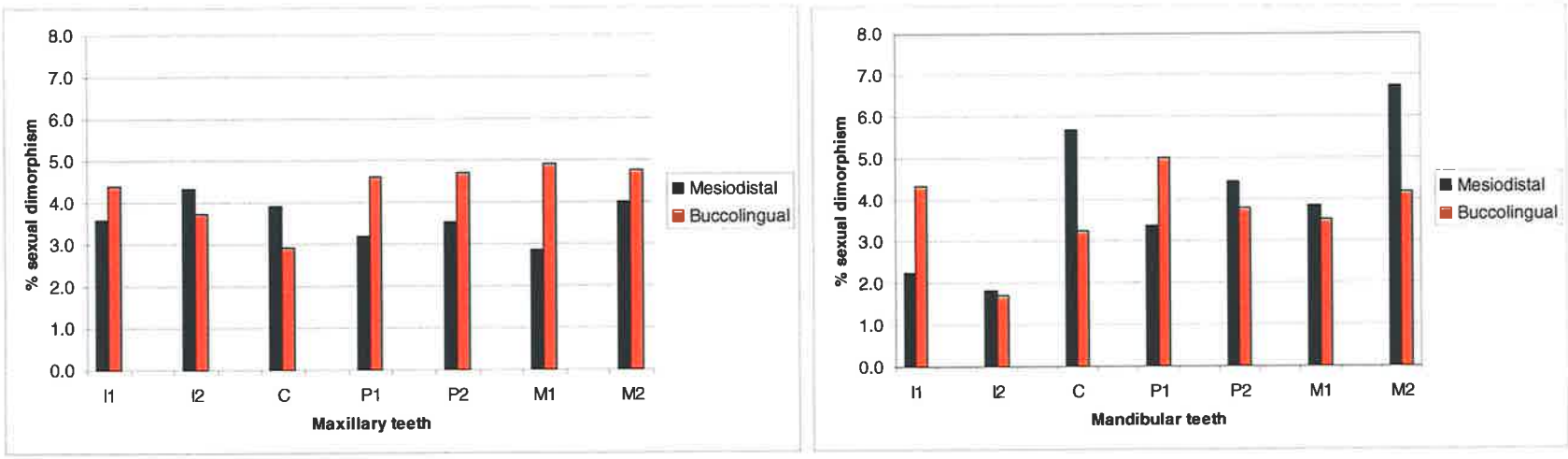


Figure 4.4 Sexual dimorphism in tooth size measurements of Chinese

Table 4.13 Basic descriptive statistics and sexual dimorphism for permanent tooth size in Indians

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Maxilla													
Mesiodistal															
I1	77	8.56	0.46	5.4	71	8.80	**	0.32	3.7	148	8.67	0.42	4.8	S	2.8
I2	75	6.91	0.55	8.0	70	7.01		0.46	6.5	145	6.96	0.51	7.3	NS	1.3
C	73	7.66	0.41	5.4	68	7.96	**	0.39	4.9	141	7.80	0.43	5.5	NS	3.9
P1	76	7.16	0.35	4.9	71	7.28	*	0.35	4.8	147	7.22	0.35	4.9	NS	1.8
P2	70	6.79	0.29	4.3	69	6.93	*	0.38	5.5	139	6.86	0.35	5.0	S	2.1
M1	74	10.37	0.52	5.0	69	10.57	*	0.55	5.2	143	10.46	0.54	5.2	NS	1.9
M2	59	10.01	0.63	6.3	58	10.28	*	0.64	6.3	117	10.15	0.65	6.4	NS	2.7

Table 4.13 (continued)

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Maxilla													
Buccolingual															
I1	73	7.08	0.51	7.2	67	7.37	**	0.45	6.2	140	7.21	0.50	7.0	NS	4.1
I2	67	6.45	0.55	8.5	65	6.60		0.43	6.5	132	6.53	0.50	7.6	NS	2.3
C	71	7.80	0.54	6.9	62	8.12	**	0.54	6.6	133	7.95	0.56	7.0	NS	4.1
P1	75	9.34	0.44	4.7	72	9.69	**	0.47	4.8	147	9.51	0.49	5.1	NS	3.8
P2	75	9.20	0.51	5.6	68	9.62	**	0.46	4.7	143	9.40	0.53	5.6	NS	4.5
M1	77	11.18	0.59	5.3	70	11.54	**	0.45	3.9	147	11.35	0.56	4.9	NS	3.2
M2	71	10.75	0.67	6.2	65	11.17	**	0.63	5.6	136	10.95	0.68	6.2	NS	3.9

Table 4.13 (continued)

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Mandible													
Mesiodistal															
I1	76	5.43	0.33	6.2	73	5.52		0.28	5.1	149	5.47	0.31	5.7	NS	1.8
I2	76	5.91	0.36	6.0	72	6.07	*	0.35	5.8	148	5.99	0.36	6.0	NS	2.6
C	74	6.62	0.31	4.7	72	6.99	**	0.37	5.3	146	6.81	0.39	5.7	NS	5.6
P1	76	7.19	0.42	5.8	72	7.30		0.32	4.4	148	7.24	0.38	5.2	NS	1.4
P2	72	7.22	0.44	6.2	68	7.38	*	0.40	5.4	140	7.30	0.43	5.9	NS	2.3
M1	75	11.06	0.53	4.8	69	11.33	**	0.56	4.9	144	11.19	0.56	5.0	NS	2.4
M2	47	10.29	0.63	6.1	42	10.50		0.50	4.7	89	10.39	0.58	5.6	NS	2.1

Table 4.13 (continued)

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean		SD	CV	N	Mean	SD	CV		
		Mandible													
Buccolingual															
I1	69	5.89	0.48	8.2	67	6.03		0.36	6.0	136	5.96	0.43	7.3	NS	2.4
I2	72	6.18	0.41	6.7	68	6.25		0.40	6.3	140	6.21	0.41	6.5	NS	1.2
C	65	7.04	0.54	7.7	52	7.21		0.47	6.5	117	7.11	0.52	7.2	NS	2.4
P1	74	8.07	0.47	5.8	69	8.19		0.44	5.3	143	8.13	0.45	5.6	NS	1.6
P2	75	8.63	0.49	5.7	72	8.84	*	0.49	5.5	147	8.73	0.50	5.7	NS	2.4
M1	74	10.69	0.48	4.5	71	10.97	**	0.46	4.2	145	10.83	0.49	4.5	NS	2.6
M2	68	10.34	0.57	5.6	62	10.65	**	0.50	4.7	130	10.49	0.56	5.3	NS	3.0

N, sample size; SD, standard deviation; CV, coefficient of variation (% SD/mean); % sex dimorphism; (mean male-mean female/mean female)100; S, equal variances not assumed; NS; equal variances assumed; *, $p<0.05$; **, $p<0.01$

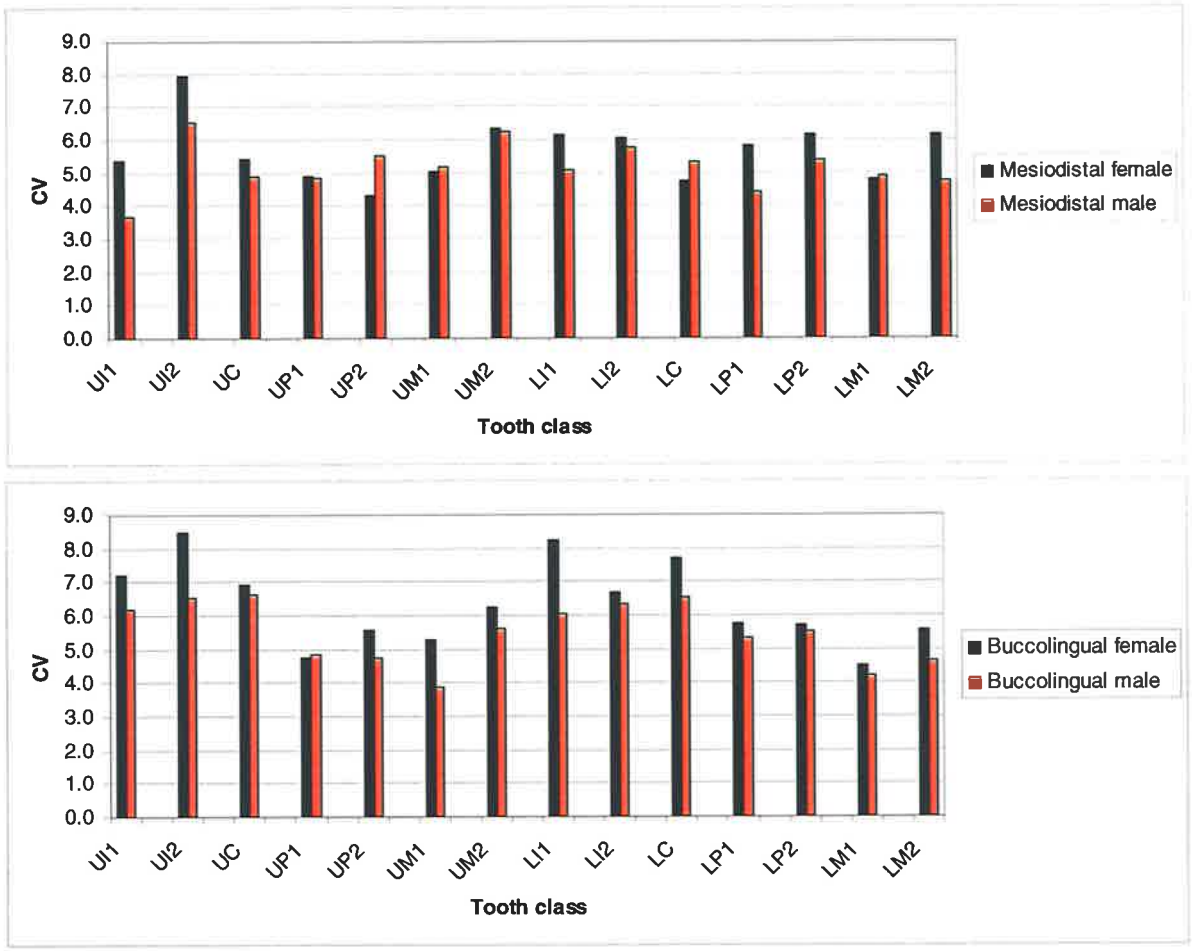


Figure 4.5 Relative variability in tooth size of Indians

*, $p<0.05$

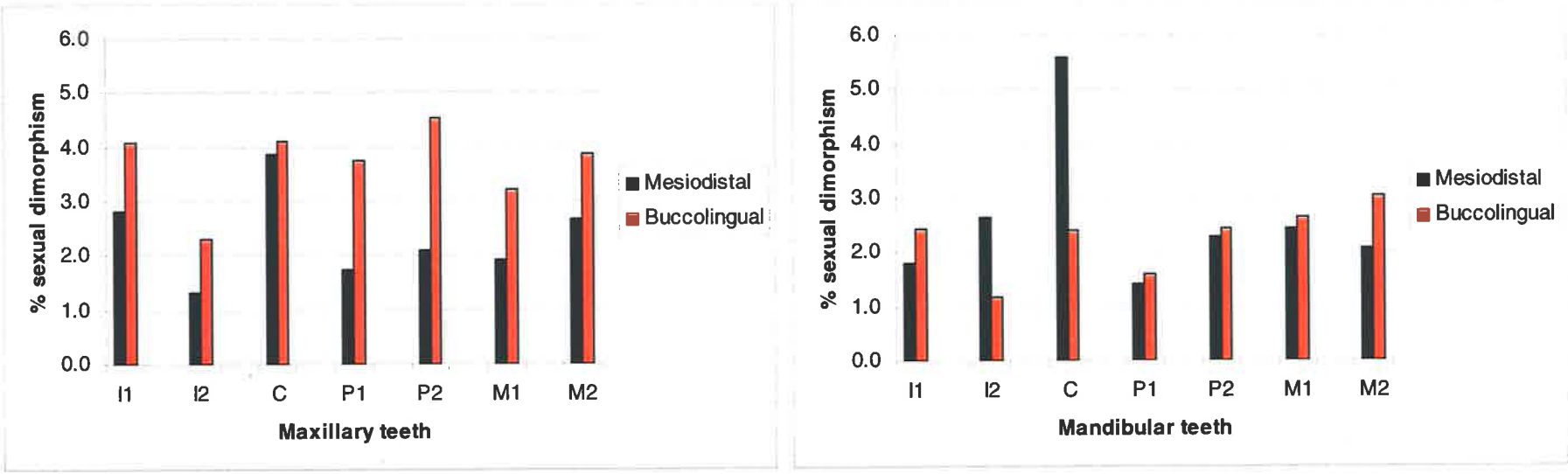


Figure 4.6 Sexual dimorphisms in tooth size of Indians

Table 4.14 Basic descriptive statistics and sexual dimorphism for permanent tooth size in Jahai

Tooth	Females				Males					Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean	SD	CV		N	Mean	SD	CV		
		Maxilla													
Mesiodistal															
I1	25	8.29	0.54	6.5	21	8.60	0.48	5.6		46	8.43	0.53	6.3	NS	3.7
I2	25	6.64	0.52	7.9	24	7.03	0.50	7.1	*	49	6.83	0.54	8.0	NS	5.9
C	27	7.65	0.40	5.3	25	7.93	0.43	5.4	*	52	7.78	0.43	5.6	NS	3.7
P1	28	7.21	0.40	5.5	26	7.17	0.38	5.3		54	7.19	0.39	5.4	NS	-0.6
P2	26	6.86	0.35	5.1	21	6.80	0.27	4.0		47	6.83	0.32	4.6	NS	-0.9
M1	25	10.28	0.46	4.5	22	10.58	0.55	5.2	*	47	10.42	0.52	5.0	NS	3.0
M2	27	9.80	0.49	5.0	24	9.95	0.52	5.3		51	9.87	0.51	5.1	NS	1.5

Table 4.14 (continued)

Tooth	Females				Males					Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean	SD	CV		N	Mean	SD	CV		
		Maxilla													
Buccolingual															
I1	21	7.13	0.58	8.2	12	7.47	0.42	5.6		33	7.26	0.55	7.6	NS	4.7
I2	18	6.40	0.35	5.5	13	6.72	0.54	8.1		31	6.53	0.46	7.1	NS	5.1
C	24	8.30	0.35	4.2											
P1	22	9.35	0.41	4.4	16	9.41	0.55	5.8		38	9.38	0.47	5.0	NS	0.6
P2	24	9.39	0.44	4.7	16	9.47	0.51	5.4		40	9.42	0.46	4.9	NS	0.8
M1	18	11.30	0.37	3.3	11	11.97	0.50	4.2	**	29	11.55	0.53	4.6	NS	5.9
M2	21	11.05	0.64	5.8	13	11.35	0.68	6.0		34	11.17	0.66	5.9	NS	2.7

Table 4.14 (continued)

Tooth	Females				Males					Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean	SD	CV		N	Mean	SD	CV		
		Mandible													
Mesiodistal															
I1	25	5.30	0.28	5.2	21	5.45	0.28	5.2		46	5.37	0.29	5.4	NS	2.8
I2	29	6.05	0.47	7.8	23	6.19	0.42	6.8		52	6.11	0.45	7.4	NS	2.3
C	28	6.85	0.35	5.1	23	7.28	0.49	6.7	**	51	7.04	0.47	6.6	NS	6.3
P1	28	7.16	0.51	7.1	22	7.10	0.39	5.5		50	7.13	0.46	6.4	NS	-0.8
P2	27	7.16	0.37	5.2	22	7.03	0.34	4.8		49	7.10	0.36	5.0	NS	-1.8
M1	22	11.01	0.53	4.8	20	11.35	0.49	4.4	*	42	11.17	0.53	4.8	NS	3.0
M2	24	10.02	0.50	5.0	19	9.93	0.64	6.4		43	9.98	0.56	5.6	NS	-0.9

Table 4.14 (continued)

Tooth	Females				Males				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV		
		Mandible												
Buccolingual														
I1														
I2														
C														
P1	18	7.95	0.60	7.5	15	8.00	0.42	5.3	33	7.97	0.52	6.5	NS	0.5
P2	16	8.38	0.53	6.3	16	8.49	0.57	6.7	32	8.44	0.54	6.5	NS	1.3
M1	15	10.53	0.51	4.8	16	10.79	0.66	6.1	31	10.66	0.59	5.6	NS	2.5
M2	18	10.45	0.57	5.5	17	10.60	0.61	5.8	35	10.52	0.59	5.6	NS	1.4

N, sample size; SD, standard deviation; CV, coefficient of variation (% SD/mean); % sex dimorphism ; (mean male-mean female/mean female)100; S, equal variances not assumed; NS, equal variances assumed; *, $p<0.05$; **, $p<0.01$

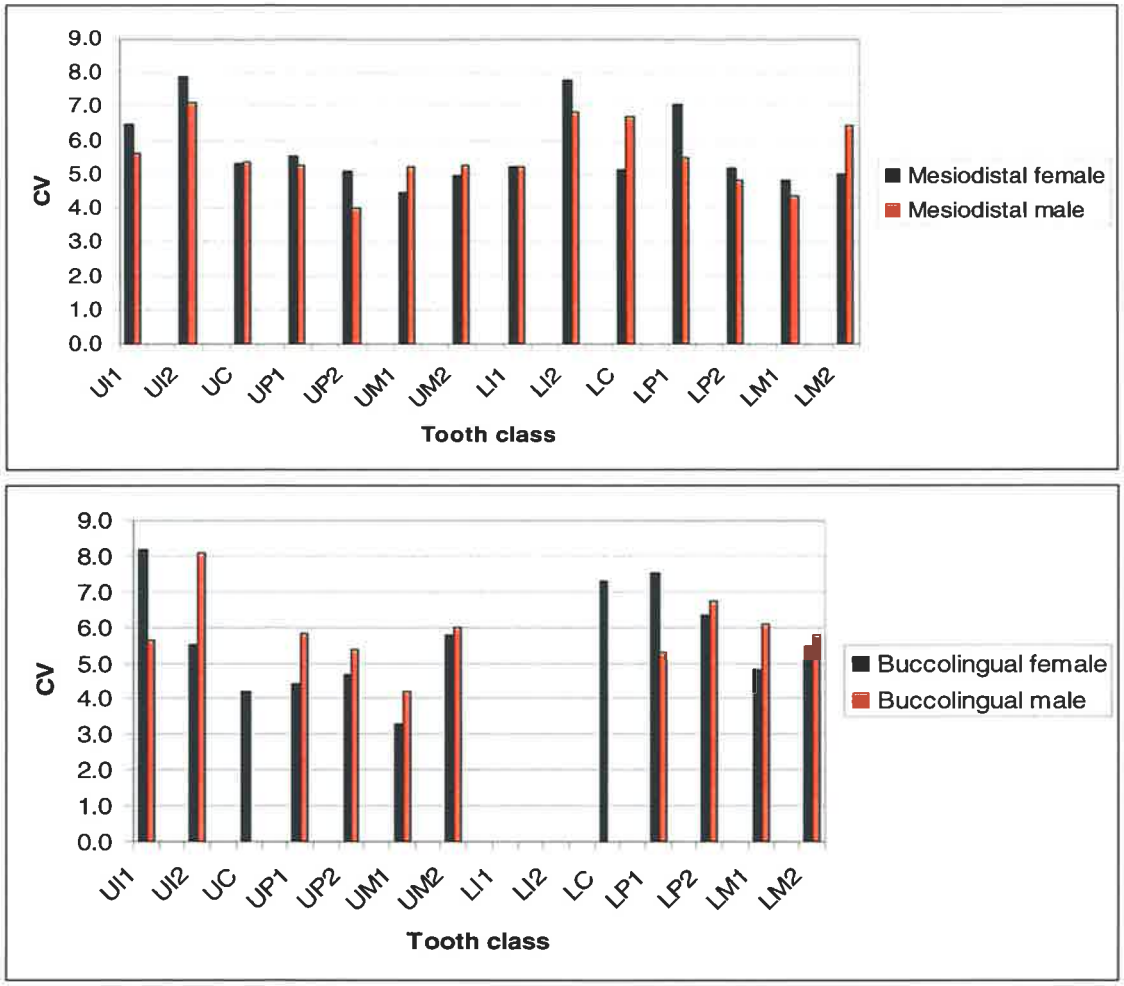


Figure 4.7 Relative variability in tooth size of Jahai

*, $p<0.05$

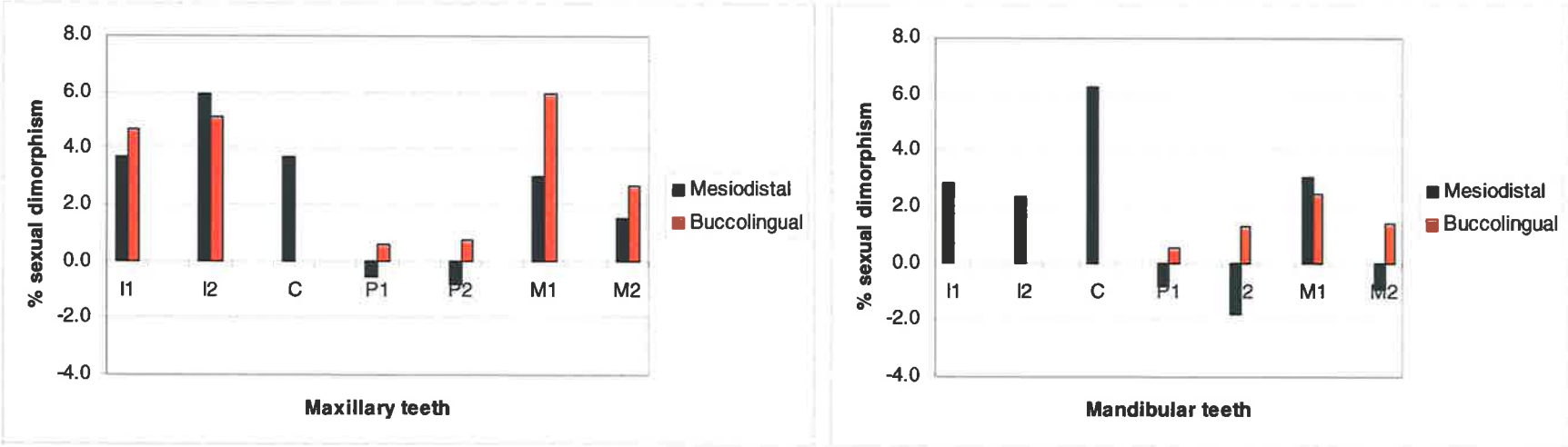


Figure 4.8 Sexual dimorphism in tooth size of Jahai

Table 4.15 Percentages dimorphism values in mesiodistal and buccolingual crown in different human populations

	Australian Aborigines[o]		Aleuts[1]		Javanese[2]		Japanese[2]		Jats (Indian)[3]		South Chinese[4]	
	MD	BL	MD	BL[a]	MD	BL	MD	BL	MD	BL©	MD φ	BL
Average dimorphism percent	3.3	4.2	2.9	2.5	3.4	-	3.0	-	3.0	3.3	1.9	-

Φ, excluding second molars; ©, excluding anterior teeth; [a], excluding central and lateral incisors
[o], (Townsend and Brown, 1979)
[1], (Moorrees, 1957)
[2], (Garn *et al.*, 1967b)
[3], (Kaul and Prakash, 1984)
[4], (Yuen *et al.*, 1997)

Filipinos[5]		Malays		Chinese		Indians		Jahai	
MD	BL	MD	BL	MD	BL	MD	BL	MD	BL*
2.5	2.8	2.4	3.6	3.8	4.0	2.5	3.0	1.9	2.6

*, excluding upper canine for males, and lower anterior and canine for both sexes
[5], (Potter *et al.*, 1981)-right side only

Table 4.16 Relative different size of the mesiodistal dimensions of maxillary upper lateral/central incisor among ethnic groups

Ethnicity	Males	Females
Malays	0.81	0.82
M'sian Chinese	0.83	0.82
Indians	0.80	0.81
Jahai	0.82	0.80
*Filipino	0.81	0.81
*American White	0.76	0.77
*Nasioi	0.86	0.86
*United Kingdom Chinese	0.82	0.83

*, (Potter *et al.*, 1981)
M'sia, Malaysia

Table 4.17 Molar size sequences among different ethnic groups

	Malays		Chinese		Indians		Jahai	
Mesiodistal	Males	Females	Males	Females	Males	Females	Males	Females
	N (%)		N (%)		N (%)		N (%)	
UM2<UM1	59 (89.4)	57 (87.7)	41 (77.4)	44 (84.6)	39 (70.9)	38 (67.9)	16 (80.0)ғ	21(87.5)
UM2>UM1	6 (9.1)	8 (12.3)	12 (22.6)	8 (15.4)	15 (27.3)	17 (30.3)	4 (20.0)	3(12.5)
UM1=UM2	1 (1.5)	0 (0.0)	0 (0.0)	0 (0.0)	1 (1.8)	1 (1.8)	0 (0.0)	0 (0.0)
Total	66	65	53	52	55	56	20	24
LM2<LM1	55 (96.5)	54 (100.0)	40 (93.0)ғ	41 (97.6)	37 (92.5)ғ	41 (91.1)	17 (100.0)	19(95.0)
LM2>LM1	2 (3.5)	0 (0.0)	3 (7.0)	1 (2.4)	3 (7.5)	3 (6.7)	0 (0.0)	1(5.0)
LM1=LM2	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (2.2)	0 (0.0)	0 (0.0)
Total	57	54	43	42	40	45	17	20

Table 4.17 (continued)

	Australian Aboriginals[a]		American Whites[a]		American Blacks[a]	
Mesiodistal	Males	Females	Males	Females	Males	Females
	N (%)		N (%)		N (%)	
UM2<UM1	221 (70.8)	229 (72.5)	83 (55.0)	118 (59.0)	63 (68.0)	62 (63.0)
UM2>UM1	80 (25.6)	69 (21.8)	52 (35.0)	62 (31.0)	17 (19.0)	24 (24.0)
UM1=UM2	11 (3.5)	18 (5.7)	15 (10.0)	19 (10.0)	12 (13.0)	13 (13.0)
Total	312	316	148	199	92	99
LM2<LM1	283 (81.3)	226 (72.9)	108 (89.0)	146 (85.0)	46 (70.0)	51 (66.0)
LM2>LM1	47 (13.5)	61 (19.7)	9 (7.0)	23 (13.0)	12 (19.0)	18 (23.0)
LM1=LM2	18 (5.2)	23 (7.4)	4 (3.0)	4 (2.0)	7 (11.0)	8 (11.0)
Total	348	310	121	173	65	77

[a], data from (Townsend and Brown, 1983); ꜰ, Fisher's exact test for sex dimorphism; *, $p<0.05$ for sex dimorphism; **, $p<0.05$ for inter-group relationship

Table 4.18 Matrix of Penrose shape coefficients for three ethnic groups (pooled-sex data)

	Malays	Chinese	Indians
Malays	-	0.022322	0.044253
Chinese	0.022322	-	0.071694
Indians	0.044253	0.071694	-

28 variables were used

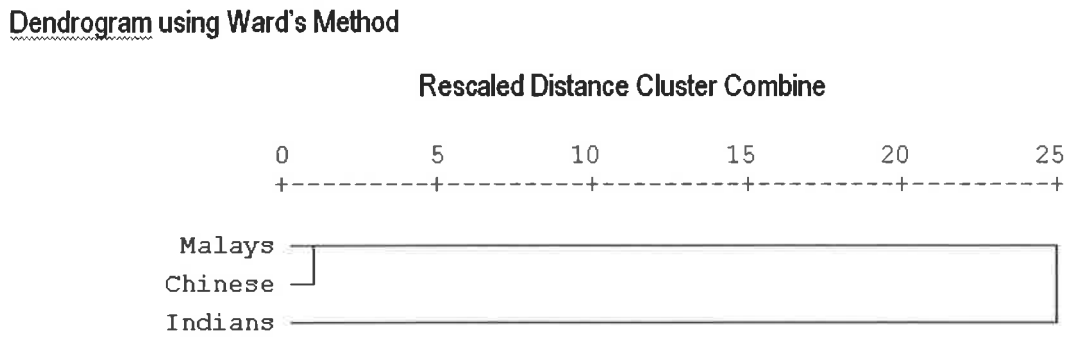


Figure 4.9 Dendrogram of three Malaysian ethnic groups

Table 4.19 Matrix of Penrose shape coefficients for four ethnic groups (pooled-sex data)

	Malays	Chinese	Indians	Jahai
Malays	-	0.02395	0.040397	0.064303
Chinese	0.02395	-	0.064814	0.097989
Indians	0.040397	0.064814	-	0.091255
Jahai	0.064303	0.097989	0.091255	-

24 variables were used

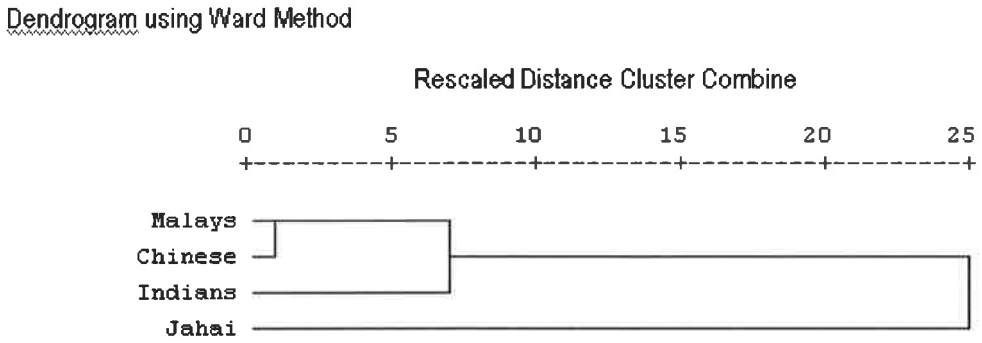


Figure 4.10 Dendrogram of four Malaysian ethnic groups

4.4 Discussion

Overall, sample sizes for Malays, Chinese and Indians were satisfactory to provide 80% power for this study. The sample size for the Jahai was limited. Therefore, the emphasis for Jahai group at this stage has been to assess patterns and trends rather than assessing the outcomes of statistical tests within- and between-groups.

Assessments of normality of the data took into account the results from several statistical analyses. The results indicated that the number of non-normal variables was relatively small, therefore, parametric tests were used for the majority of metric analyses, except for some asymmetry variables in the Jahai sample. Wilcoxon Sign Rank tests yielded results which were consistent with paired t-tests. Method error was small and comparable with other published material (Townsend and Brown, 1979; Yuen *et al.*, 1997; Chiu and Donlon, 2000). The observed error variation was smaller than three percent for all variables tested, which was accepted as reasonable (Houston, 1983). Thus, the measurement data acquired were considered to be sufficiently reliable for use in the study. Young participants who were mainly from secondary school provided reasonable sample sizes taking into account the inclusion criteria, unlike the older participants in the Jahai group. Some variables in this group had to be omitted from the analyses due to interproximal and occlusal wear, calculus and caries.

Many researchers have used only one side of the dentition in their analyses and assumed tooth crown dimensions are symmetrical (Hanihara, 1976; Sharma, 1983; Harris and Rathbun, 1989; Hanihara and Ishida, 2005; Matsumura and Hudson, 2005). Potter *et al.* (1981) showed that several antimeric pairs in Filipinos displayed significant differences in crown size and commented that this could indicate true asymmetry. The range of mean differences for antimeric pairs that displayed significant differences in size in this study was 0.05-0.25mm. This raised concerns about whether averaging values from both sides or measuring one side only was justified. Therefore, in order to be sure, preliminary analyses were conducted. The mean differences in all four ethnic groups were small despite several variables being significant at $p<0.05$. The differences were comparable to the magnitude of measurement error, that is 0.04-0.07mm. Hence, it was considered that the differences were unlikely to be of biological importance and that it was justifiable to take measurements taken from one side only as in other previous studies (Macko *et al.*, 1979; Townsend and Brown, 1979; Axelsson and Kirveskari, 1983; Yuen *et al.*, 1997).

Dimensional variability studies in the Malaysian samples showed that anterior teeth tended to be more variable than posterior teeth. This finding is similar to that in Southern Chinese populations (Hanihara, 1976; Yuen *et al.*, 1997). The dimensional variability within morphological classes in the current Chinese sample was consistent with the well-known morphogenetic gradients UI2>UI1, P2>P1, LI1>LI2, and M2>M1 (Dahlberg, 1945; Townsend and Brown, 1981), while the Malay, Indian and Jahai samples revealed some exceptions, particularly in the lower incisors and premolars. A number of other populations have also shown these exceptions, including Icelanders (Kirveskari *et al.*, 1978); Mexican Indians (O'Rourke and Crawford, 1980); Australian Aborigines, Japanese, Ainu, American Negro (Hanihara, 1976). Patterning in tooth size, with few exceptions, followed the rule of field theory in the upper incisor and molar classes. The only exception was one variable in the Jahai female sample, the buccolingual diameter of upper incisors, where the distal tooth was less variable than the central incisor. This rare outcome had also been reported by Kieser *et al.* (1985) and Harris and Nweeia (1980). The coefficient of variability for the mesiodistal diameter of the lower first molar in the Indian male group was higher than for the second molar. A similar pattern was found in female Australian Aborigines (Hanihara, 1976).

Kieser and Preston (1981) and Kieser *et al.* (1985) inclined towards the clonal theory to explain dimensional variability patterns in the premolar and lower incisor classes. In addition to clonal theory, O'Rourke and Crawford (1980) suggested 'lability factors' to explain variability P1>P2 in premolars field. According to the concept of lability factors, the two premolars lost during mammalian evolution were the two mesial premolars. Hence, dimensional variability trends of P1>P2 may not be unexpected.

Sofaer *et al.* (1971), Sofaer *et al.* (1972) and Mizoguchi (1983) suggested that the distal tooth normally requires a longer period of time to grow which exposes it more to environmental influences. In terms of premolars, there is a possibility of population variation in the growth of the mesial and distal premolar teeth (P1 and P2). Perhaps the completion of calcification of the distal tooth occurs earlier than that of the mesial tooth in these populations in contrast to the first and second molars, where the timing of completion of calcification is clearly distinguished. This could explain the pattern observed in the molar class.

Dimensional variability patterns in Malays and Chinese failed to show any evidence of differences between the sexes, which was similar to observations by Lunt (1967) and Perzigian (1976) and Yuen *et al.* (1997). However, dimensional variability has been reported to differ between males and females in Indians and Jahai. The dimensional variability in Indians suggested that females were more variable in the mesiodistal and buccolingual diameters while

in Jahai sample, males were more variable than females in buccolingual diameters. Sexual dimorphism in dimensional variability was also found in a Ticuna population, with females more variable for mesiodistal diameters in both arcades while males were more variable in buccolingual diameters in the maxilla (Harris and Nweeia, 1980). Townsend and Brown (1979) found tooth size in males was more variable than in females, whereas Garn *et al.* (1968b) and Kirveskari *et al.* (1978) reported the reverse.

Consistent patterns of sexual dimorphism were found in the four ethnic groups studied. The majority of teeth in males were larger than in females, which agrees with reported results in other populations (Moorrees, 1957; Perzigian, 1976; Townsend and Brown, 1979; Axelsson and Kirveskari, 1983; Yuen *et al.*, 1996; Yuen *et al.*, 1997). The canine tooth was the most sexually dimorphic tooth found in this study, and incisors were the least. These findings are also consistent with other published results (Moorrees, 1957; Garn *et al.*, 1966; Garn *et al.*, 1967a; Garn *et al.*, 1967b; Hanihara, 1976; Townsend and Brown, 1979; Potter *et al.*, 1981; Iscan, 1989)

None of the four ethnic groups showed evidence to support canine field theory, even though this theory proposed by Garn *et al.* (1964) received some attention from Garn *et al.* (1966), Garn *et al.* (1968b), Turner (1969), Axelsson and Kirveskari (1983) and Harris and Bailit (1988). Comparable results rejecting the theory have been published by Perzigian (1976), Kirveskari *et al.* (1978), Kaul and Prakash (1981), Kieser *et al.* (1985), Harris and Bailit (1988), Iscan (1989) and Yuen *et al.* (1997).

Generally, buccolingual diameters were more dimorphic than mesiodistal diameters in all groups studied, which was consistent with the findings of Moorrees (1957), Townsend and Brown (1979), and Harris and Nweeia (1980), although Perzigian (1976) and Iscan (1989) reported contradictory results. Lunt (1967) found no sex differences between diameters.

Sexual dimorphism patterns favored mandibular teeth in the Malays and Chinese, but maxillary teeth in the Indians. No clear pattern of sexual dimorphism between arches was observed in the Jahai sample. Iscan (1989) suggested that mandibular teeth were more dimorphic than maxillary teeth, but only one tooth was statistically significant at the 5% level in their study. The variation in pattern of sexual dimorphism between arches could be due to some degree of genetic independence between the arches (Potter *et al.*, 1976).

The use of percentages (Garn *et al.*, 1964) to quantify sexual dimorphism was criticized by Marini *et al.* (1999). The authors stressed the need to take account of the variation within males and females in studies of sexual dimorphism. They found that the use of univariate t-tests and Kolmogorov Smirnov tests produced more stable results than use of

percentages. In this study both methods, percent sexual dimorphism and t-tests, were used and no conflicting results were observed. Furthermore, to avoid redundancy and type I error, it has been suggested that multivariate analyses should be used (Potter, 1972; Kieser *et al.*, 1985; Chiu and Donlon, 2000). Multivariate analyses of sexual dimorphism will be presented and discussed in the next chapter.

Tratman (1950), Lasker and Lee (1957) and Potter *et al.* (1981) used the relative size of lateral and central incisors as a racial marker. According to Tratman (1950), South East Asian populations have relatively large lateral incisors compared to central incisors when comparisons are made with other populations. In this study, the ratios calculated were not consistent with this claim. The Indian sample, who were considered by Tratman (1950) to have an Indo-european ancestry, were found to have a similar ratio as other Mongoloid samples. Two points can tentatively be deduced from this study. Firstly, the ratio of lateral incisor/central incisor size would be strongly influenced by the high variability in mesiodistal size of the lateral incisors, giving the size ratio a low value for taxonomic studies. Secondly, there is always the possibility that some genetic mixture may have occurred between samples.

The results for the Malaysian samples showed that the frequencies of molar size sequence (MSS) M1>M2 were comparable with other modern human populations (Townsend and Brown, 1983). Sofaer *et al.* (1971) suggested that the distal molar reduced first in the process of evolution towards simplification and modernization. There were variations within the Malaysian samples with only Malay-Indian paired (sexes pooled) comparisons giving significant differences (chi-square=13.18; d.f.=1; p=0.000). The overall pattern of relationships was not consistent with predicted population relationships, thus supporting a study by Axelsson and Kirveskari (1983) that MSS has low taxonomic value.

Differences in the frequencies of M1>M2 in the maxilla and mandible were apparent in all Malaysian groups with the sequence being more common in the mandible. Similar findings have been reported in the Indian Knoll collection (Perzigian, 1976), Australian Aborigines (Townsend and Brown, 1983) and African Caucasoids (Kieser *et al.*, 1985). To explain these trends, LeBlanc and Black (1974) have hypothesized that the maxillary molar occlusal surface has reduced in size twice as much as the mandibular molar, and Coon (1962) suggested that the maxillary first molar received more selective pressure for smaller tooth size than the mandibular molar.

Frequencies of M1>M2 and M2>M1 did not show sexual dimorphism in the maxilla or mandible. This result was also found in Ticuna Indians (Harris and Nweeia, 1980) and African

Caucasoids (Kieser *et al.*, 1985) while sexual dimorphism was observed only in the mandible in Australian Aborigines (Townsend and Brown, 1983).

The pattern of affinities presented in the Malaysian groups may be explained by the immigration model or dual layer model (Jacob, 1967). Close affinities between Malays and Chinese are expected according to this model. This relationship reflects a long history of phylogeny and Mongoloidization. This relationship is also consistent with the suggestions of Bellwood (1978), and Turner (1987, 1990) that Malays and Chinese have common ancestors. The Indian situation could be explained by some degree of mixture, since these three groups live close together despite socio-cultural and religious barriers, but still be consistent with Tratman's (1950) classification. Tratman (1950) classified both Malays and Chinese under the Mongoloid grouping, and Indians in an Indoeurasian grouping. The Negritos (Jahai) fit with Bellwood (1978) model, suggesting that the modern Negritos are successors of Australo-melanesians who survived Mongoloidization from the southern migration of northern Mongoloids. According to Bellwood (1978), they survived Mongoloidization because they lived in mountainous areas and had gone through selection pressure for small body build, which enabled survival in a harsh environment. In contrast, Hanihara (1992b) proposed that the Negritos (Jahai) were predecessors of Sundadonts, which would mean the Malays and Negritos should be clustered together since they are both Sundadonts. In essence, my findings are more consistent with the dual layer model or immigration model (Matsumura and Majid, 1999; Hanihara and Ishida, 2005; Matsumura and Hudson, 2005) than the local evolution model (Turner, 1987; Turner, 1990; Hanihara, 1992a; Hanihara, 1992b). However, to conclusively state which model best fits the situation by only observing four modern ethnic groups would be premature.

The findings from phenetic distance patterns allow the conclusion to be made that Penrose shape data derived from dental crown measurements are suitable for taxonomic studies. This is consistent with Hanihara and Ishida (2005), who found that odontometric data were suitable to characterize and study population variation at the regional level. In contrast, Hooijer (1950), Harris and Nweeia (1980), and Falk and Corruccini (1982) have argued for use of odontometry in anthropological studies. Close affinity between Malays and Chinese might hamper discrimination accuracy between these groups but it may still be possible to discriminate Indians from Malays and Chinese. The Jahai group was represented by a small sample size which leads to limitations for multivariate discriminant analyses. The degree and pattern of sexual dimorphism in each ethnic group offers an additional potential forensic application to the ability to predict sex using odontometric data.

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Chapter 5 Sexual dimorphism in tooth size in Malaysian populations

5.1. Introduction

Odontometric differences between males and females are reported to be only around 3-4% (Kieser, 1990). These average differences are far less than the magnitude of sexual dimorphism observed in primates, but several researchers have shown promising applications for sex identification in archaeology and forensic situations, with the success rates ranging from 71 to 93% (Ditch and Rose, 1972; Garn *et al.*, 1977; Sciulli *et al.*, 1977; Brown and Townsend, 1979; Garn *et al.*, 1979; Potter *et al.*, 1981; Kieser *et al.*, 1985; Haeussler *et al.*, 1989). It has also been shown that additional variables do not necessarily improve the prediction rate significantly (Brown and Townsend, 1979; Garn *et al.*, 1979).

Several authors have reported that the mandibular canine is the most sexually dimorphic tooth based on univariate and multivariate analyses (Sciulli *et al.*, 1977; Brown and Townsend, 1979; Potter *et al.*, 1981; Iscan and Kedici, 2003). However, variables selected as highly sexual dimorphic in univariate analyses have not always been selected as strongly discriminative in multivariate analyses (Potter *et al.*, 1981; Kieser *et al.*, 1985).

The application of odontometry for sex prediction is made possible with more understanding of the influence of the sex chromosomes and sex hormones on tooth crown size. Much of the knowledge of sex chromosomal effects on tooth crown size has been derived from studies of individuals with sex chromosome aneuploidies. These investigations have shown that the X-chromosome influences enamel thickness (Alvesalo and Tammisalo, 1981; Alvesalo *et al.*, 1987) while the Y-chromosome has an effect on both enamel and dentine thickness (Alvesalo and Tammisalo, 1985; Alvesalo *et al.*, 1991). Several studies have shown that dentine thickness is the determinant factor for sexual dimorphism (Stroud *et al.*, 1994; Harris and Hicks, 1998; Shields, 2000; Schwartz and Dean, 2005). Studies of opposite sex dizygotic twins have indirectly revealed the effect of sex hormones, by showing larger tooth size in females of opposite sex twin pairs than sister-sister monozygotic twins (Dempsey *et al.*, 1999).

Knowing the sex of an individual is an important step in reconstructing identity. The use of odontometric methods is obviously only applied in cases where the sex organs and other secondary sexual characteristics are not available for analysis. Currently, there are no reference studies for sex prediction using odontometric data in Malaysian populations. Since

there is obvious population variation in the pattern and magnitude of sexual dimorphism e.g. (Garn *et al.*, 1967; Hanihara, 1978; Haeussler *et al.*, 1989), this aspect of the thesis aims to fulfil the forensic and legal requirements of success rates and reproducibility for these populations.

For this methodology to be widely accepted by the forensic community, it is of utmost importance that it provides a low error rate so that the technique can be accepted in court. For example, the case of Daubert v. Merrell Dow Pharmaceuticals (Daubert, 1993) emphasizes the importance of applying a sound and valid scientific technique for forensic analyses. In addition, the models developed should also be used in real forensic situations.

5.2. Materials and methods

Abbreviations

BL	Buccolingual diameter
MD	Mesiodistal diameter
SMEAN	Replace missing values with mean group
RL	Tooth size was measured on the right side (left tooth measurement will be taken if right tooth was excluded)
U1	upper central incisor
U2	upper lateral incisor
U3	upper canine
U4	upper first premolar
U5	upper second premolar
U6	upper first molar
U7	upper second molar
L1	lower central incisor
L2	lower second incisor
L3	lower canine
L4	lower first premolar
L5	lower second premolar
L6	lower first molar
L7	lower second molar

Examples:

SMEAN(RL_U1_MD)	Tooth size measured on the right side in mesiodistal diameter of upper central incisor replace missing values with group mean
SMEAN(RL_U1_BL)	Tooth size measured on the right side in buccolingual diameter of upper central incisor replace missing values with group mean
SMEAN(RL_ L1_MD)	Tooth size measured on the right side in mesiodistal diameter of lower central incisor replace missing values with group mean

The descriptions of samples, inclusion and exclusion criteria, measurement methods and errors are provided in Chapters 3 and 4. Additional tooth size data, which were measured after the completion of measurements of samples reported in Chapter 3, were included to provide test samples. The test sample data were used only for validating classification

accuracy. The sizes of the test samples were as follows: 32 Malays (16 males: 16 females), 33 Chinese (14 males: 19 females) and 34 Indians (17 males: 17 females). There was no test sample for the Jahai since the available sample was limited in size. Missing data were replaced with mean values (separate values for males and females) for each ethnic group to maintain the ratio of sample size to number of dependent variables (predictors). To avoid complexity in the analyses, approximately equal sample sizes for males and females were used in each ethnic group. The majority of the data were normally distributed (Appendices 5.1, 5.2, 5.3, 5.4, 5.7, 5.8, 5.10) with no obvious outliers ($z<4.0$). For each group in this study, the sample size met the minimum expectation of being at least 20 or larger than the number of predictor variables (Hair *et al.*, 1995).

Two types of statistical analyses were chosen for this study; general linear modeling (GLM) multivariate analysis of variance (Gardner, 2001) and discriminant function analysis (Hair *et al.*, 1995). In GLM, the collective contribution of all 28 variables to sexual dimorphism was assessed statistically by Pillai's Trace. If Pillai's Trace was significant, then interpretation of univariate F-values could proceed. GLM analyses took into account Type 1 error, thus direct interpretation for each predictor can be made at $p<0.05$ (Gardner, 2001). GLM can also calculate the power of the study to detect differences between males and females for every predictor.

Discriminant function analyses use one or several predictors to generate a linear equation that discriminates two categorical groups. The equation is as follows:

$Z= W_1X_1+ W_2X_2 +...+ W_iX_i$

where

Z= discriminant score

W_i=discriminant weight for independent variable i

X_i=independent variable i

This analysis encompasses two main objectives; to determine the most discriminative independent (predictor) variables and to establish procedures for classifying groups using selected variables from stepwise and forced entry procedures.

Discriminant functions were calculated using the stepwise method which is based on entering independent variables one at a time untill a set of the most efficient variables discriminating sex is determined. At the initial stage of computation, independent variables with the largest F-value derived from univariate analysis of variance are entered into the function computations. This process is followed by the process of retaining or removing the predictor variables at default settings $F=3.84$ to enter and $F=2.71$ to remove. The combination of

remaining predictors in the function was tested by Wilk's Lambda, a multivariate test of significance and presented as a table of canonical discriminant functions. The smaller the Wilk's Lambda value, the more likely a group is different from the others. The chi-square transformation of Wilk's Lambda was utilized to test significance at $p<0.10$. The squared canonical correlation explained the proportion of total variation attributed by the combination of predictors in the function to the differences between groups. The function was considered "appropriate" if it was significant. The discriminant loadings indicated the amount of contribution of each predictor to the discriminant function, whether the predictor was retained or removed from the function after stepwise procedure.

After identifying discriminative variables, the accuracy of the function must be tested. Three methods are available to validate the classification accuracy or hit ratio. The first method uses the data that have been used to generate the discriminant function. This will introduce upward bias to the hit ratio. Another method is the "leave one out" procedure (L-O-O) or U-method where each case in the analysis is classified by the functions derived from all cases other than that case (SPSS Inc., 1989-2001). The third method involves using a test sample which had not been included in the generation of the discriminant function. This test sample serves as an external validation of the functions.

Considering the practical forensic application, several combinations of predictor variables were used as input into the discriminant function analyses. The outcome varied with different inputs. The first input used all 28 variables (except Jahai, where only 14 mesiodistal variables were used). The second approach used selected variables as input in the stepwise procedure, such as all mesiodistal diameters, or all buccolingual diameters, or all maxillary teeth and all mandibular teeth. Individual single predictor variables were also included, using a forced entry procedure. In addition to exploring specific group prediction models, an input using pooled ethnic data (which did not include Jahai due to small sample size), was attempted to produce non-specific prediction models. The process followed the procedure for exploring specific-ethnic group prediction models.

From the linear discriminant function, Z, the calculated discriminant score was compared to the cutting score to determine group classifications. The cutting score is the average of the two centroids. The classification accuracy was further tested by determining if the achievement was better than chance. Two methods were used; proportion chance criterion and Press's Q statistic. The hit ratio should be larger than the proportion chance criterion for the outcome to be better than chance. The formula for the proportion chance criterion is as follows:

$C_{PRO} = p^2 + (1-p)^2$

C_{PRO} = the proportion chance criterion

p = proportion of case in group 1

1-p = proportion of case in group 2

Press's Q statistic was derived using total sample size, number of correct classifications and number of groups involved. The calculated value was then compared against a critical value of 3.84 (derived from a Chi-square table with one degree of freedom and alpha level at 5%). If the calculated Q value was larger than the critical value, the predictions were better than chance. The formula was as follows:

$$\text{Press's } Q = \frac{(N-(n*K))^2}{N(K-1)}$$

N = total sample size

n = number of observations correctly classified

K = number of groups

Similar steps of analysis were used for sex prediction in Malays, Chinese, Indians, Jahai, and for pooled ethnic groups. Therefore, detailed analyses of the stepwise procedures and coefficients of discriminant functions are presented in tabular form in this Chapter for Malays only. Tables for the other populations are presented as Appendices to avoid repetition.

5.3. Results

5.3.1. Malays

All data were normally distributed (Appendices 5.1 and 5.2). None of the variables showed skewness or a kurtosis/standard error ratios of more than two. Two outliers, cases 164 and 173, were associated with z-scores between 3.0 and 3.2. All correlations were significant at the 5% level and the coefficients ranged from 0.24 to 0.79, which confirmed the linearity of the dependent variables.

Table 5.1 shows the female Malay sample was slightly larger than males but no more than 1.5 times. The sample sizes in each group were more than 20 and exceeded the number of dependent variables. Tests of multivariate effects from general linear modeling-multivariate procedures suggested that the collection of 28 tooth size variables differed between the sexes (Pillai's Trace value is 0.481; F (28, 129) = 4.272, $p<0.001$ and the power of detecting true difference at 5% was 100%). Table 5.2 shows the univariate effects derived from general linear modeling (GLM) multivariate procedures, indicating significant difference at $p<0.05$ between males and females for 22 dependent variables. The range of power observed for these 22 variables was from 58.1% to 100% with 16 variables having 90% or more the power of detecting true difference at alpha 5%. Ranking of sexual dimorphism using F-value indicated that the mesiodistal diameter of upper and lower canines was the most sexually dimorphic dimension, while the mesiodistal diameter of upper second premolars was the least dimorphic. In general, buccolingual dimensions were more dimorphic than mesiodistal dimensions.

Stepwise methods using Mahalanobis D^2 selected the six most discriminative dependent variables (ie, the Mahalanobis distance between the groups was maximized) which were all mesiodistal dimensions; upper lateral incisor, upper canine, upper first and second premolar, upper second molar, and lower canine (Table 5.3). Wilk's Lambda values and minimum D^2 values confirmed the significant contribution of each of the six variables that remained after stepwise enter/remove procedures. Discriminant function comprising these six variables was strongly significant (chi-square=81.2; df=6; $p<0.000$) and 41.2% of the variance in sexual dimorphism could be explained by this function. Table 5.4 presents the unstandardized coefficients and constants for generating linear discriminant functions which produced discriminant scores for each case (Z_i). The linear discriminant function formula for sex prediction in Malays was as follows:

Z = -15.62 - 0.741(UI2_MD) + 1.366(UC_MD) - 1.144(UP1_MD) - 0.918(UP2_MD) + 0.897(UM2_MD) + 2.273(LC_MD).

The average of group centroids, 0.0425, acted as a cutting score to determine grouping. Predictive accuracy provided a hit ratio rate of 82.3% for the original sample, 79.1% for the leave one out (L-O-O) procedure, and 75.0% for the test sample (Table 5.5).

Predictive classification accuracy was validated by using two methods; proportion chance criterion and Press's Q statistic. The classification accuracy shown in Table 5.5 was better than the proportional chance criterion of 50.1% for analysis sample and L-O-O procedure, and 50.0% for the test sample. Press's Q indicated all prediction results were better than chance with Press's Q values as follows: original sample, 65.8; test sample, 8.0; leave-one-out sample, 53.6; all of which were larger than the critical value of 3.84. A list of discriminant functions is given in Table 5.6. Several single tooth variables could potentially be used; the mesiodistal diameter of upper canine and lower canine, as well as the mesiodistal diameter of lower second molar and buccolingual diameter of the upper second molar. Other combinations, which could potentially be used in real forensic situations, like input data using all mesiodistal diameter variables and input data using all mesiodistal diameters in the mandible are also presented.

5.3.2. Chinese

Nearly all data were distributed normally (Appendices 5.3 and 5.4). Several values were identified as outliers ($3.0<|z|<3.5$); cases 288 LM2 MD, 322 UM2 BL, 326 LC MD, 293 LP2 BL, 364 UI2 BL, and 237 LM2 MD. All variables were associated with weak to moderate coefficients of correlation and all correlations were significant at $p<0.01$.

General linear modeling confirmed multivariate effects on sexual dimorphism (Pillai's Trace=0.566; $F(28, 115)=5.360$; $p<0.000$ and 100% power to detect true difference). Table 5.8 shows the univariate effects for 28 predictor variables. Twenty-four variables were highly significant with power of more than 81% to detect difference for each predictor. Only one variable, LI2 MD, was not significant ($p\geq0.05$). The mesiodistal diameter of the lower second molar was identified as most dimorphic, while the mesiodistal diameter of the lower lateral incisor was least dimorphic. There was no apparent pattern in sexual dimorphism between mesiodistal and buccolingual dimensions.

Stepwise methods identified only two highly discriminative variables; the mesiodistal diameter of the lower second molar and the buccolingual diameter of the lower first premolars (Appendix 5.17). 40.4% of the total variance was accounted for by this function. Wilk's lambda

confirmed significant discrimination using these two variables collectively (chi-square= 73.01; d.f.=2; p<0.000). The cutting score was determined to lie at - 0.0345 from averaging the centroids, with discriminant scores less than - 0.0345 belonging to females (Appendix 5.18). Unstandardized coefficients and constants presented in Appendix 5.18 were used to construct the linear discriminant function, Z= 1.788(LM2_MD) + 1.036(LP1_BL) - 27.33. Table 5.9 provides the classification hit ratios as follows: 83.3% original sample, 81.8% test sample, 82.6% L-O-O procedures. Females performed better than males in all three procedures. Further testing confirmed a hit ratio better than chance from the two tests: proportion chance criterion and Press's Q. From proportion chance criterion, a 50.1% or less hit ratio could be achieved by chance and 51.1% for test sample. The Press's Q values were 64.0 for the original sample, 61.4 for L-O-O, 13.4 for the test sample, which were all larger than critical value of 3.84. Table 5.10 provides a list of discriminant functions that could be used in different forensic situations. The majority of the functions generated high hit ratios.

5.3.3. Indians

All data were normally distributed except for significant kurtosis shown by the mesiodistal diameter of the lower second molar in both males and females (Appendices 5.5 and 5.6). Several outliers were detected; cases 528 LC BL, 481 LM2 MD, 408 LM2 MD, 427 LM2 MD, ($3.0 < |z| < 3.7$). Three pairs of correlations were insignificant at 5%, with values of 0.14, 0.15 and 0.16.

General linear modeling-multivariate analysis of variance provided an analysis of the collective effects of 28 variables on sexual dimorphism (Pillai's Trace = 0.420; F(28, 122) = 3.161, p<0.000). Table 5.12 shows the mesiodistal diameter of the lower canine was the most dimorphic dimension, while the mesiodistal diameter of the upper lateral incisor was the least dimorphic. Fourteen variables were identified to have more than 80% power to detect true difference between the sexes. Twenty-two variables were significant at p<0.05. Appendix 5.20 shows stepwise methods that selected four predictors; mesiodistal dimensions of the lower canine, lower first premolar and upper lateral incisor, and the buccolingual diameter of the upper second premolar, which were confirmed by Wilk's Lambda and Mahalanobis D^2. Only 33.2% of the total variance was accounted by this function. However, Wilk's Lambda confirmed the significance of this function (chi-square=59.30; df=4; p<0.000). Appendix 5.21 shows the coefficients and constants for each of the tooth dimensions used to construct linear discriminant functions. Individual cases with a discriminant score less than the cutting score, 0.047, were assigned as female.

Table 5.13 shows a classification hit ratio of 74.8% in the original sample, 73.5% in the test sample, and 73.5% in L-O-O procedure. From Press's Q, all hit ratio results were better than chance (critical Press's Q value of 3.84; alpha=0.05; d.f. =1). The Press's Q values were 37.25 for the original sample; 33.38 for L-O-O; and 7.53 for the test sample. Proportion chance criterion indicated the minimum hit ratio for analysis and L-O-O samples was 50.1% and for the test sample 50.0%. A list of discriminant functions is given in Table 5.14. The overall hit ratio was not as good as in the Chinese but four functions obtained values greater than 72% in original, test and L-O-O samples. Some teeth showed a strong contribution to sex discrimination, namely the mesiodistal diameter of lower second molar and the lower canine.

5.3.4. Jahai

Only mesiodistal data were used for the analyses of the Jahai sample. Normality testing revealed no violation except significant kurtosis in males for the upper second molar in the mesiodistal diameter (Appendices 5.7 and 5.8). A couple of variables were identified as outliers with z-scores equal to 2.6 case 601, UM2 MD; and case 558, LC MD. Nine pairs of bivariate correlations were not significant at 5%; L7 MD-LI1 MD (0.12), L5 MD-LC MD (0.20), L5 MD-UI2 MD (0.10), L5 MD-UC MD (0.12), L5 MD-UM1 MD (0.13), LI1 MD-UP2 MD (0.17), UM2 MD-UI2 MD (0.17), LI1 MD-UM2 MD (0.03), LI1 MD-UP2 MD (0.17).

General linear modeling-multivariate analysis of variance procedure indicated that the collective effects of 14 predictors on sexual dimorphism were significant (Pillai's Trace = 0.565; $F(14, 40)= 3.715$; $p<0.001$). Seven variables were significant at 0.05 and the power of detecting true difference ranged from 57% - 97.3% (Table 5.16). Stepwise methods identified two predictor variables, the mesiodistal dimension of lower canine and lower second molar as the most discriminative variables (Appendix 5.23). The predictors were found to contribute significantly to the separation of sexes as indicated by Wilk's Lambda and Mahalanobis D^2. A function which comprised two predictors was found to be highly significant (Chi-square=24.804; d.f.=2; $p<0.000$). The function explained only 37.9% of the variance in sexual dimorphism. Appendix 5.24 shows the list of coefficients and constants for the linear dicriminant function. Discriminant scores less than 0.042 were assigned as female. Table 5.17 shows hit ratios greater than 80% for sex discrimination. Proportion chance criterion and Press's Q indicated that the hit ratio was better than chance. The minimum hit ratio due to chance was less than 50.1% for both original and L-O-O samples. Press's Q values for the original and L-O-O procedure were as follows: 24.9 and 19.8 respectively. Table 5.18 reveals similar discriminative

variables to those displayed in Table 5.17, using different inputs. Sex discrimination was dominated by the mesiodistal diameter of the lower canine and the lower second molar.

5.3.5. Sex prediction using data from three ethnic groups

The male and female sample sizes were approximately equal. All data were normally distributed, except the buccolingual diameter of lower incisors in females (positively skewed) and positive kurtosis for the mesiodistal diameter of lower second molars in both sexes (positive kurtosis) (Appendices 5.9 and 5.10). No outliers were detected based on z-scores larger than 4.0. Bivariate correlation analysis showed that pairwise associations of all variables were significant at $p<0.01$. The values of correlation coefficients ranged from 0.25 to 0.78.

General linear modeling–multivariate analysis of variance procedure showed that the collective effects from 28 predictors were significant (Pillai's Trace=0.400; $F(28, 424)=10.077$; $p<0.000$). Table 5.20 shows that all predictors were significant at the 0.05 level and the power to detect sexual dimorphism was more than 87.0%. The mesiodistal dimension of the lower canine was the most dimorphic variable while the mesiodistal diameter of the upper lateral incisor was the least. The overall pattern of ranking of sexual dimorphism indicated that after the canine, second molars were strongly dimorphic as well.

Appendix 5.26 shows that 12 variables remained after stepwise procedures. The selection was confirmed by significant findings in Wilk's Lambda and Mahalanobis D^2. 38.7% of the variance was explained by combination of these predictors. The function was confirmed to be significant (Wilk's Lambda= 0.613; chi-square=217.60; d.f.=12; $p<0.000$). Appendix 5.27 shows the unstandardized and group centroids for constructing linear discriminant functions. A discriminant score less than 0.0085 was assigned as female. Classification accuracy showed that the performance in the original, test and L-O-O samples was as follows: 77.3%, 81.8% and 75.7% respectively (Table 5.21). The accuracy of performance was better than chance in all cases as indicated by the proportion chance criterion and Press's Q statistic. Proportion chance criterion indicated a 50.0% hit ratio could be obtained by chance for the original and L-O-O samples, and 50.1% for the test sample. Press's Q statistic showed that the critical values were 134.7, 119.8 and 40.1 for the original, L-O-O and test samples respectively. Assessment hit ratios within each ethnic group (Table 5.22) using the same discriminant function as in the Table 5.21, did not reveal large differences in hit ratios between Malays, Chinese and Indians. Table 5.23 shows a list of discriminant functions based on different input variables. All functions provided hit ratios which were better than chance but only two functions produced hit ratio above 74%.

5.3.6. Univariate vs multivariate analyses

Appendices 5.16, 5.19, 5.22, 5.25 and 5.28 show the order of predictor variables based on their loadings was comparable with F-values in Tables 5.2, 5.8, 5.12, 5.16 and 5.20. However, the order of sexual dimorphism based on univariate analysis did not necessarily indicate that variables associated with higher F values would be retained in the function as the most discriminative predictors. There were several predictors selected in functions which came from intermediate or lower rank based on their loadings.

5.3.7. Practical approach

Tables 5.6, 5.10, 5.14, 5.18, 5.23 show several possible combinations of discriminant functions chosen to meet realistic demands in forensic practice. Overall, the results were satisfactory, in that, for each group, several alternatives of discriminant functions performed as well as when all 28 predictors were computed in stepwise methods. Examples of using linear discriminant functions for sex prediction are given in an Appendix 5.29.

Table 5.1 Descriptive statistics for tooth size in Malays

Tooth	Sex	N	Mean	Std. Deviation	Tooth	Sex	N	Mean	Std. Deviation
				Mesiodistal					
UI1	Females	83	8.50	0.54	LI1	Females	83	5.44	0.32
	Males	75	8.70	0.45		Males	75	5.56	0.36
	Total	158	8.59	0.51		Total	158	5.49	0.34
UI2	Females	83	7.00	0.64	LI2	Females	83	6.06	0.38
	Males	75	7.08	0.57		Males	75	6.14	0.34
	Total	158	7.04	0.61		Total	158	6.10	0.36
UC	Females	83	7.81	0.48	LC	Females	83	6.77	0.38
	Males	75	8.27	0.42		Males	75	7.21	0.40
	Total	158	8.03	0.51		Total	158	6.98	0.45
UP1	Females	83	7.44	0.41	LP1	Females	83	7.28	0.41
	Males	75	7.52	0.42		Males	75	7.43	0.45
	Total	158	7.48	0.42		Total	158	7.36	0.44
UP2	Females	83	6.99	0.43	LP2	Females	83	7.32	0.44
	Males	75	7.03	0.42		Males	75	7.39	0.45
	Total	158	7.01	0.43		Total	158	7.35	0.45
UM1	Females	83	10.53	0.47	LM1	Females	83	11.35	0.45
	Males	75	10.68	0.51		Males	75	11.66	0.49
	Total	158	10.60	0.49		Total	158	11.49	0.49
UM2	Females	83	9.90	0.54	LM2	Females	83	10.28	0.53
	Males	75	10.16	0.45		Males	75	10.58	0.59
	Total	158	10.02	0.52		Total	158	10.42	0.57
				Buccolingual					
UI1	Females	83	7.13	0.47	LI1	Females	83	5.75	0.34
	Males	75	7.41	0.47		Males	75	5.96	0.33
	Total	158	7.26	0.49		Total	158	5.85	0.35
UI2	Females	83	6.45	0.43	LI2	Females	83	6.14	0.35
	Males	75	6.75	0.45		Males	75	6.30	0.44
	Total	158	6.59	0.46		Total	158	6.21	0.40
UC	Females	83	7.93	0.50	LC	Females	83	7.12	0.45
	Males	75	8.29	0.51		Males	75	7.51	0.55
	Total	158	8.10	0.54		Total	158	7.31	0.54
UP1	Females	83	9.49	0.46	LP1	Females	83	7.99	0.42
	Males	75	9.77	0.49		Males	75	8.28	0.52
	Total	158	9.62	0.49		Total	158	8.13	0.49
UP2	Females	83	9.40	0.53	LP2	Females	83	8.56	0.43
	Males	75	9.60	0.53		Males	75	8.81	0.39
	Total	158	9.50	0.54		Total	158	8.68	0.43
UM1	Females	83	11.18	0.48	LM1	Females	83	10.81	0.44
	Males	75	11.61	0.55		Males	75	10.99	0.49
	Total	158	11.38	0.56		Total	158	10.89	0.47
UM2	Females	83	11.05	0.59	LM2	Females	83	10.44	0.43
	Males	75	11.41	0.69		Males	75	10.83	0.56
	Total	158	11.22	0.66		Total	158	10.63	0.53

Table 5.2 Tests of between-subject effects in Malays

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	P	Observed Power	Rank of sex dimorphism
Sex	SMEAN(RL_U1_MD)	1.625	1	1.625	6.446	0.012	0.713	18
	SMEAN(RL_U2_MD)	0.266	1	0.266	0.721	0.397	0.135	27
	SMEAN(RL_U3_MD)	8.350	1	8.350	40.789	0.000	1.000	2
	SMEAN(RL_U4_MD)	0.310	1	0.310	1.810	0.181	0.267	24
	SMEAN(RL_U5_MD)	0.071	1	0.071	0.389	0.534	0.095	28
	SMEAN(RL_U6_MD)	0.917	1	0.917	3.832	0.052	0.494	23
	SMEAN(RL_U7_MD)	2.766	1	2.766	10.994	0.001	0.909	16
	SMEAN(RL_U1_BL)	3.247	1	3.247	14.777	0.000	0.969	11
	SMEAN(RL_U2_BL)	3.466	1	3.466	17.792	0.000	0.987	7
	SMEAN(RL_U3_BL)	5.200	1	5.200	20.151	0.000	0.994	6
	SMEAN(RL_U4_BL)	3.098	1	3.098	13.847	0.000	0.959	13
	SMEAN(RL_U5_BL)	1.512	1	1.512	5.374	0.022	0.635	20
	SMEAN(RL_U6_BL)	7.265	1	7.265	27.491	0.000	0.999	3
	SMEAN(RL_U7_BL)	5.162	1	5.162	12.539	0.001	0.941	14
	SMEAN(RL_L1_MD)	0.586	1	0.586	5.157	0.025	0.617	21
	SMEAN(RL_L2_MD)	0.207	1	0.207	1.608	0.207	0.243	25
	SMEAN(RL_L3_MD)	7.624	1	7.624	49.687	0.000	1.000	1
	SMEAN(RL_L4_MD)	0.886	1	0.886	4.738	0.031	0.581	22
	SMEAN(RL_L5_MD)	0.199	1	0.199	1.001	0.319	0.169	26
	SMEAN(RL_L6_MD)	3.789	1	3.789	17.199	0.000	0.985	8
	SMEAN(RL_L7_MD)	3.525	1	3.525	11.391	0.001	0.918	15
	SMEAN(RL_L1_BL)	1.779	1	1.779	15.630	0.000	0.976	9
	SMEAN(RL_L2_BL)	1.071	1	1.071	6.918	0.009	0.743	17
	SMEAN(RL_L3_BL)	5.981	1	5.981	23.497	0.000	0.998	5
	SMEAN(RL_L4_BL)	3.399	1	3.399	15.519	0.000	0.975	10
	SMEAN(RL_L5_BL)	2.435	1	2.435	14.376	0.000	0.965	12
	SMEAN(RL_L6_BL)	1.223	1	1.223	5.668	0.018	0.658	19
	SMEAN(RL_L7_BL)	6.037	1	6.037	24.524	0.000	0.998	4

Table 5.3 Summary of stepwise discriminant analysis results in Malays

Step	Variables entered	Wilks' Lambda		Min. D Squared		Between Groups
		Lambda	Significance	Statistic	Significance	
1	SMEAN(RL_L3_MD)	0.7584	0.0000	1.2611	0.0000	Female and Male
2	SMEAN(RL_U2_MD)	0.7083	0.0000	1.6304	0.0000	Female and Male
3	SMEAN(RL_U3_MD)	0.6630	0.0000	2.0124	0.0000	Female and Male
4	SMEAN(RL_U4_MD)	0.6327	0.0000	2.2986	0.0000	Female and Male
5	SMEAN(RL_U7_MD)	0.6066	0.0000	2.5676	0.0000	Female and Male
6	SMEAN(RL_U5_MD)	0.5882	0.0000	2.7725	0.0000	Female and Male

At each step, the variable that maximizes the Mahalanobis distance between the two closest groups is entered.

a Maximum number of steps is 56.

b Minimum partial F to enter is 3.84.

c Maximum partial F to remove is 2.71.

d F level, tolerance, or VIN insufficient for further computation.

Canonical discriminant function

Function	Eigenvalue	Canonical Correlation	Wilks' Lambda	chi-square	df	Sig.
1	0.7002	0.642	0.588	81.205	6	0.000

a First 1 canonical discriminant functions were used in the analysis.

Table 5.4 Unstandardized discriminant function coefficients and group centroids in Malays

	Function 1
SMEAN(RL_U2_MD)	-0.7413
SMEAN(RL_U3_MD)	1.3659
SMEAN(RL_U4_MD)	-1.1437
SMEAN(RL_U5_MD)	-0.9176
SMEAN(RL_U7_MD)	0.8968
SMEAN(RL_L3_MD)	2.2733
(Constant)	-15.6195

Unstandardized coefficients

Functions at Group Centroids

Sex	Function 1
Females	-0.7904
Males	0.8747

Unstandardized canonical discriminant functions evaluated at group means

Table 5.5 Classification accuracy for sex prediction in Malays

				Predicted Group Membership		Total
			Sex	Females	Males	
Cases Selected	Original	Count	Females	68	15	83
			Males	13	62	75
		%	Females	81.9	18.1	100.0
			Males	17.3	82.7	100.0
	Cross-validated	Count	Females	66	17	83
			Males	16	59	75
		%	Females	79.5	20.5	100.0
			Males	21.3	78.7	100.0
Cases Not Selected	Original	Count	Females	13	3	16
			Males	5	11	16
		%	Females	81.3	18.8	100.0
			Males	31.3	68.8	100.0

82.3% of selected original grouped cases correctly classified.
75.0% of unselected original grouped cases correctly classified.
79.1% of selected cross-validated grouped cases correctly classified.

Table 5.6 List of discriminant function in Malays

Input	Variables	Coefficients[1]	Contrasts	Hit Ratio (%)			Validation						Cutting score
							Proportion Chance Criterion			Press's Q			
				Original	Test	L-O-O	Original	Test	L-O-O	Original	Test	L-O-O	
	UI1 MD	1.992	-17.112	62.7	50.0	62.7	B	N	B	S	NS	S	0.010
	UI2 MD	1.646	-11.586	56.3	68.8	56.3	B	B	B	NS	S	NS	0.003
	UC MD	2.210	-17.749	70.3	68.8	70.3	B	B	B	S	S	S	0.026
	UP1 MD	2.415	-18.060	56.3	56.3	56.3	B	B	B	NS	NS	NS	0.006
	UP2 MD	2.344	-16.424	50.0	56.3	50.0	N	B	N	NS	NS	NS	0.002
	UM1 MD	2.044	-21.677	57.0	56.3	57.0	B	B	B	NS	NS	NS	0.008
	UM2 MD	1.994	-19.982	65.2	65.6	65.2	B	B	B	S	NS	S	0.013
	UI1 BL	2.133	-15.495	60.1	62.5	60.1	B	B	B	S	NS	S	0.016
	UI2 BL	2.266	-14.939	64.6	59.4	64.6	B	B	B	S	NS	S	0.017
	UC BL	1.968	-15.944	65.8	40.6	65.8	B	N	B	S	NS	S	0.019
	UP1 BL	2.114	-20.334	62.0	62.5	62.0	B	B	B	S	NS	S	0.015
	UP2 BL	1.885	-17.903	55.1	59.4	54.4	B	B	B	NS	NS	NS	0.010
	UM1 BL	1.945	-22.140	67.7	65.6	67.7	B	B	B	S	NS	S	0.021
	UM2 BL	1.559	-17.489	60.8	75.0	60.8	B	B	B	S	S	S	0.014
	LI1 MD	2.966	-16.299	58.2	46.9	58.2	B	N	B	S	NS	S	0.009
	LI2 MD	2.789	-17.007	56.3	37.5	56.3	B	N	B	NS	NS	NS	0.005
	LC MD	2.553	-17.814	71.5	71.9	70.9	B	B	B	S	S	S	0.029
	LP1 MD	2.313	-17.013	57.0	50.0	57.0	B	N	B	NS	NS	NS	0.009
	LP2 MD	2.243	-16.499	54.4	59.4	54.4	B	B	B	NS	NS	NS	0.004
	LM1 MD	2.131	-24.488	65.8	53.1	65.8	B	B	B	S	NS	S	0.017
	LM2 MD	1.798	-18.736	67.7	81.3	67.7	B	B	B	S	S	S	0.014
	LI1 BL	2.964	-17.344	65.8	65.6	65.8	B	B	B	S	NS	S	0.016
	LI2 BL	2.541	-15.791	67.1	56.3	67.1	B	B	B	S	NS	S	0.011
	LC BL	1.982	-14.480	69.6	53.1	69.6	B	B	B	S	NS	S	0.020
	LP1 BL	2.137	-17.374	62.0	59.4	62.0	B	B	B	S	NS	S	0.016
	LP2 BL	2.430	-21.081	64.6	56.3	64.6	B	B	B	S	NS	S	0.015

Table 5.6 (continued)

Input	Variables	Coefficients[1]	Contrasts	Hit Ratio (%)			Validation						Cutting score
							Proportion Chance Criterion			Press's Q			
				Original	Test	L-O-O	Original	Test	L-O-O	Original	Test	L-O-O	
	LM1 BL	2.153	-23.458	57.0	56.3	57.0	B	B	B	NS	NS	NS	0.010
	LM2 BL	2.015	-21.416	68.4	75.0	68.4	B	B	B	S	S	S	0.020
All MD maxilla	UC MD	2.641	-14.879	74.1	62.5	73.4	B	B	B	S	NS	S	0.029
	UI2 MD	-0.899											
All MD mandible	LI2 MD	-1.673	-11.973	72.2	84.4	72.2	B	B	B	S	S	S	0.033
	LC MD	3.178											
All BL maxilla	UC BL	0.955	-23.254	67.1	59.4	67.1	B	B	B	S	NS	S	0.024
	UM1 BL	1.363											
All BL mandible	LC BL	1.207	-22.377	69.6	65.6	69.0	B	B	B	S	NS	S	0.025
	LM2 BL	1.276											
All MD	UI2 MD	-0.741	-15.620	82.3	75.0	79.1	B	B	B	S	S	S	0.043
	UC MD	1.366											
	UP1 MD	-1.144											
	UP2 MD	-0.918											
	UM2 MD	0.897											
	LC MD	2.273											
All BL	UM1 BL	1.265	-22.208	69.0	53.1	67.7	B	B	B	S	NS	S	0.024
	LC BL	1.069											

[1], Canonical discriminant function coefficients (unstandardized); B, better than chance; N, not better; S, significant at 5%; NS, not significant at 5%

Table 5.7 Descriptive statistics for tooth size in Chinese

Tooth	Sex	N	Mean	Std. deviation	Tooth	Sex	N	Mean	Std. deviation
				Mesiodistal					
UI1	Females	69	8.60	0.46	LI1	Females	69	5.48	0.32
	Males	75	8.91	0.48		Males	75	5.60	0.32
	Total	144	8.76	0.49		Total	144	5.54	0.33
UI2	Females	69	7.09	0.56	LI2	Females	69	6.07	0.31
	Males	75	7.39	0.55		Males	75	6.18	0.35
	Total	144	7.25	0.57		Total	144	6.13	0.33
UC	Females	69	8.06	0.42	LC	Females	69	6.89	0.38
	Males	75	8.38	0.48		Males	75	7.29	0.41
	Total	144	8.23	0.48		Total	144	7.10	0.44
UP1	Females	69	7.52	0.42	LP1	Females	69	7.33	0.37
	Males	75	7.76	0.40		Males	75	7.58	0.36
	Total	144	7.64	0.43		Total	144	7.46	0.39
UP2	Females	69	7.05	0.40	LP2	Females	69	7.25	0.44
	Males	75	7.30	0.43		Males	75	7.58	0.42
	Total	144	7.18	0.43		Total	144	7.42	0.46
UM1	Females	69	10.37	0.51	LM1	Females	69	11.21	0.51
	Males	75	10.67	0.46		Males	75	11.65	0.41
	Total	144	10.53	0.50		Total	144	11.44	0.51
UM2	Females	69	9.89	0.51	LM2	Females	69	10.14	0.42
	Males	75	10.31	0.44		Males	75	10.82	0.49
	Total	144	10.11	0.52		Total	144	10.49	0.57
				Buccolingual					
UI1	Females	69	7.09	0.39	LI1	Females	69	5.75	0.33
	Males	75	7.41	0.46		Males	75	6.00	0.31
	Total	144	7.26	0.45		Total	144	5.88	0.35
UI2	Females	69	6.55	0.48	LI2	Females	69	6.17	0.33
	Males	75	6.79	0.48		Males	75	6.28	0.31
	Total	144	6.68	0.49		Total	144	6.23	0.32
UC	Females	69	8.10	0.47	LC	Females	69	7.23	0.47
	Males	75	8.35	0.53		Males	75	7.47	0.58
	Total	144	8.23	0.52		Total	144	7.35	0.54
UP1	Females	69	9.57	0.46	LP1	Females	69	8.06	0.35
	Males	75	10.01	0.53		Males	75	8.46	0.47
	Total	144	9.80	0.54		Total	144	8.27	0.46
UP2	Females	69	9.32	0.56	LP2	Females	69	8.59	0.38
	Males	75	9.76	0.61		Males	75	8.92	0.54
	Total	144	9.55	0.62		Total	144	8.76	0.50
UM1	Females	69	11.19	0.50	LM1	Females	69	10.75	0.44
	Males	75	11.74	0.50		Males	75	11.13	0.43
	Total	144	11.48	0.57		Total	144	10.95	0.47
UM2	Females	69	11.04	0.54	LM2	Females	69	10.41	0.46
	Males	75	11.57	0.71		Males	75	10.85	0.46
	Total	144	11.32	0.68		Total	144	10.64	0.51

Table 5.8 Tests of between-subject effects for Chinese

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Observed Power	Rank of sexual dimorphisms
Sex	SMEAN(RL_U1_MD)	3.439	1	3.439	15.732	0.000	0.976	18
	SMEAN(RL_U2_MD)	3.379	1	3.379	11.005	0.001	0.909	22
	SMEAN(RL_U3_MD)	3.643	1	3.643	17.864	0.000	0.987	15
	SMEAN(RL_U4_MD)	2.079	1	2.079	12.358	0.001	0.937	21
	SMEAN(RL_U5_MD)	2.254	1	2.254	12.937	0.000	0.947	20
	SMEAN(RL_U6_MD)	3.190	1	3.190	13.745	0.000	0.957	19
	SMEAN(RL_U7_MD)	6.246	1	6.246	27.554	0.000	0.999	8
	SMEAN(RL_U1_BL)	3.513	1	3.513	19.198	0.000	0.992	14
	SMEAN(RL_U2_BL)	2.214	1	2.214	9.617	0.002	0.869	23
	SMEAN(RL_U3_BL)	2.104	1	2.104	8.238	0.005	0.813	24
	SMEAN(RL_U4_BL)	6.997	1	6.997	28.092	0.000	1.000	7
	SMEAN(RL_U5_BL)	6.885	1	6.885	20.135	0.000	0.994	13
	SMEAN(RL_U6_BL)	10.888	1	10.888	43.824	0.000	1.000	2
	SMEAN(RL_U7_BL)	10.173	1	10.173	25.487	0.000	0.999	10
	SMEAN(RL_L1_MD)	0.553	1	0.553	5.364	0.022	0.633	26
	SMEAN(RL_L2_MD)	0.438	1	0.438	4.025	0.047	0.513	28
	SMEAN(RL_L3_MD)	5.494	1	5.494	35.028	0.000	1.000	3
	SMEAN(RL_L4_MD)	2.202	1	2.202	16.187	0.000	0.979	17
	SMEAN(RL_L5_MD)	3.736	1	3.736	20.246	0.000	0.994	12
	SMEAN(RL_L6_MD)	6.756	1	6.756	31.545	0.000	1.000	6
	SMEAN(RL_L7_MD)	16.636	1	16.636	78.832	0.000	1.000	1
	SMEAN(RL_L1_BL)	2.319	1	2.319	22.126	0.000	0.997	11
	SMEAN(RL_L2_BL)	0.431	1	0.431	4.204	0.042	0.531	27
	SMEAN(RL_L3_BL)	2.066	1	2.066	7.348	0.008	0.768	25
	SMEAN(RL_L4_BL)	5.916	1	5.916	33.704	0.000	1.000	4
	SMEAN(RL_L5_BL)	3.894	1	3.894	17.678	0.000	0.987	16
	SMEAN(RL_L6_BL)	5.137	1	5.137	27.450	0.000	0.999	9
	SMEAN(RL_L7_BL)	6.944	1	6.944	32.871	0.000	1.000	5

Table 5.9 Classification accuracy for sex prediction in Chinese

				Predicted Group Membership		Total
			Sex	Females	Males	
Cases Selected	Original	Count	Females	59	10	69
			Males	14	61	75
		%	Females	85.5	14.5	100.0
			Males	18.7	81.3	100.0
	Cross-validated	Count	Females	58	11	69
			Males	14	61	75
		%	Females	84.1	15.9	100.0
			Males	18.7	81.3	100.0
Cases Not Selected	Original	Count	Females	16	3	19
			Males	3	11	14
		%	Females	84.2	15.8	100.0
			Males	21.4	78.6	100.0

83.3% of selected original grouped cases correctly classified.
81.8% of unselected original grouped cases correctly classified.
82.6% of selected cross-validated grouped cases correctly classified.

Table 5.10 List of discriminant function in Chinese

Input	Variables	Coefficients[1]	Contrasts	Hit Ratio (%)			Validation						Cutting score
							Proportion Chance Criterion			Press's Q			
				Original	Test	L-O-O	Original	Test	L-O-O	Original	Test	L-O-O	
	UI1 MD	2.139	-18.741	62.5	66.7	62.5	B	B	B	S	NS	S	-0.014
	UI2 MD	1.805	-13.079	63.9	75.8	63.2	B	B	B	S	S	S	-0.012
	UC MD	2.215	-18.226	61.8	72.7	61.8	B	B	B	S	S	S	-0.015
	UP1 MD	2.438	-18.63	65.3	69.7	65.3	B	B	B	S	S	S	-0.012
	UP2 MD	2.396	-17.213	63.9	75.8	63.2	B	B	B	S	S	S	-0.013
	UM1 MD	2.076	-21.849	61.8	72.7	61.8	B	B	B	S	S	S	-0.013
	UM2 MD	2.100	-21.230	72.2	87.9	70.8	B	B	B	S	S	S	-0.018
	UI1 BL	2.338	-16.965	66.7	72.7	66.7	B	B	B	S	S	S	-0.016
	UI2 BL	2.084	-13.911	65.3	69.7	65.3	B	B	B	S	S	S	-0.011
	UC BL	1.979	-16.288	65.3	81.8	65.3	B	B	B	S	S	S	-0.010
	UP1 BL	2.004	-19.641	69.4	66.7	69.4	B	B	B	S	NS	S	-0.019
	UP2 BL	1.710	-16.328	65.3	72.7	64.6	B	B	B	S	S	S	-0.016
	UM1 BL	2.006	-23.032	68.1	75.8	68.1	B	B	B	S	S	S	-0.023
	UM2 BL	1.583	-17.917	72.9	72.7	72.9	B	B	B	S	S	S	-0.018
	LI1 MD	3.116	-17.269	61.1	51.5	61.1	B	B	B	S	NS	S	-0.008
	LI2 MD	3.031	-18.577	56.3	60.6	56.3	B	B	B	NS	NS	NS	-0.007
	LC MD	2.525	-17.923	69.4	81.4	69.4	B	B	B	S	S	S	-0.021
	LP1 MD	2.711	-20.227	63.2	75.8	63.2	B	B	B	S	S	S	-0.014
	LP2 MD	2.328	-17.278	66.7	75.8	66.7	B	B	B	S	S	S	-0.016
	LM1 MD	2.161	-24.715	68.1	75.8	68.1	B	B	B	S	S	S	-0.020
	LM2 MD	2.171	-22.836	80.6	84.8	80.6	B	B	B	S	S	S	-0.031
	LI1 BL	3.089	-18.156	68.1	81.8	68.1	B	B	B	S	S	S	-0.017
	LI2 BL	3.124	-19.456	61.8	75.8	61.8	B	B	B	S	S	S	-0.007
	LC BL	1.886	-13.867	61.1	69.7	61.1	B	B	B	S	S	S	-0.009
	LP1 BL	2.387	-19.740	70.8	69.7	70.8	B	B	B	S	S	S	-0.020
	LP2 BL	2.131	-18.664	68.1	72.7	68.1	B	B	B	S	S	S	-0.015

Table 5.10 (continued)

Input	Variables	Coefficients[1]	Contrasts	Hit Ratio (%)			Validation: Proportion Chance Criterion			Validation: Press's Q			Cutting score
				Original	Test	L-O-O	Original	Test	L-O-O	Original	Test	L-O-O	
	LM1 BL	2.312	-25.306	70.8	69.7	70.8	B	B	B	S	S	S	-0.018
	LM2 BL	2.176	-23.145	75.0	72.7	74.3	B	B	B	S	S	S	-0.020
All maxillary MD	UI2 MD	0.762	-23.195	72.9	81.8	72.9	B	B	B	S	S	S	-0.020
	UM2 MD	1.748											
All mandible MD	LI2 MD	-1.806	-22.787	80.6	87.9	79.9	B	B	B	S	S	S	-0.036
	LC MD	1.478											
	LM2 MD	1.806											
All MD	LI2 MD	-1.806	-22.787	80.6	87.9	79.9	B	B	B	S	S	S	-0.036
	LC MD	1.478											
	LM2 MD	1.806											
All maxilla BL	UM1 BL	2.006	-23.032	68.1	75.8	68.1	B	B	B	S	S	S	-0.023
All mandible BL	LP1 BL	1.408	-24.802	70.8	63.6	70.1	B	B	B	S	NS	S	-0.024
	LM2 BL	1.237											
All BL	LPI BL	1.177	-25.512	75.0	72.7	75.0	B	B	B	S	S	S	-0.026
	UM1 BL	1.374											

[1], Canonical discriminant function coefficients (unstandardized); B, better than chance; N, not better; S, significant at 5%; NS, not significant at 5%

Table 5.11 Descriptive statistics for tooth size in Indians

Tooth	SEX	N	Mean	Std. Deviation	Tooth	SEX	N	Mean	Std. Deviation
				Mesiodistal					
UI1	Females	78	8.56	0.46	LI1	Females	78	5.43	0.33
	Males	73	8.80	0.32		Males	73	5.52	0.28
	Total	151	8.67	0.41		Total	151	5.47	0.31
UI2	Females	78	6.91	0.54	LI2	Females	78	5.91	0.35
	Males	73	7.01	0.45		Males	73	6.07	0.35
	Total	151	6.96	0.50		Total	151	5.99	0.36
UC	Females	78	7.66	0.40	LC	Females	78	6.62	0.30
	Males	73	7.95	0.38		Males	73	6.99	0.37
	Total	151	7.80	0.41		Total	151	6.80	0.38
UP1	Females	78	7.16	0.35	LP1	Females	78	7.19	0.41
	Males	73	7.28	0.35		Males	73	7.30	0.32
	Total	151	7.22	0.35		Total	151	7.24	0.37
UP2	Females	78	6.79	0.28	LP2	Females	78	7.22	0.43
	Males	73	6.93	0.37		Males	73	7.38	0.38
	Total	151	6.86	0.33		Total	151	7.30	0.41
UM1	Females	78	10.37	0.51	LM1	Females	78	11.06	0.52
	Males	73	10.57	0.53		Males	73	11.33	0.54
	Total	151	10.46	0.53		Total	151	11.19	0.54
UM2	Females	78	10.01	0.55	LM2	Females	78	10.29	0.49
	Males	73	10.29	0.57		Males	73	10.52	0.37
	Total	151	10.15	0.58		Total	151	10.40	0.45
				Buccolingual					
UI1	Females	78	7.08	0.49	LI1	Females	78	5.89	0.46
	Males	73	7.37	0.44		Males	73	6.04	0.35
	Total	151	7.22	0.49		Total	151	5.96	0.41
UI2	Females	78	6.45	0.51	LI2	Females	78	6.18	0.40
	Males	73	6.60	0.41		Males	73	6.25	0.38
	Total	151	6.52	0.47		Total	151	6.21	0.39
UC	Females	78	7.80	0.51	LC	Females	78	7.04	0.49
	Males	73	8.12	0.50		Males	73	7.21	0.40
	Total	151	7.95	0.53		Total	151	7.12	0.46
UP1	Females	78	9.34	0.43	LP1	Females	78	8.07	0.45
	Males	73	9.69	0.46		Males	73	8.20	0.42
	Total	151	9.51	0.48		Total	151	8.13	0.44
UP2	Females	78	9.20	0.50	LP2	Females	78	8.63	0.48
	Males	73	9.62	0.44		Males	73	8.84	0.49
	Total	151	9.40	0.51		Total	151	8.73	0.50
UM1	Females	78	11.18	0.58	LM1	Females	78	10.69	0.47
	Males	73	11.54	0.44		Males	73	10.97	0.45
	Total	151	11.35	0.55		Total	151	10.82	0.48
UM2	Females	78	10.75	0.64	LM2	Females	78	10.34	0.54
	Males	73	11.18	0.59		Males	73	10.66	0.46
	Total	151	10.96	0.65		Total	151	10.49	0.52

Table 5.12 Tests of between-subject effects in Indians

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Observed Power	Rank of sexual dimorphism
Sex	SMEAN(RL_U1_MD)	2.200	1	2.200	14.110	0.000	0.962	11
	SMEAN(RL_U2_MD)	0.325	1	0.325	1.313	0.254	0.207	28
	SMEAN(RL_U3_MD)	3.306	1	3.306	21.891	0.000	0.996	4
	SMEAN(RL_U4_MD)	0.595	1	0.595	4.976	0.027	0.601	21
	SMEAN(RL_U5_MD)	0.740	1	0.740	7.002	0.009	0.748	17
	SMEAN(RL_U6_MD)	1.511	1	1.511	5.626	0.019	0.654	20
	SMEAN(RL_U7_MD)	2.830	1	2.830	8.988	0.003	0.846	14
	SMEAN(RL_U1_BL)	3.162	1	3.162	14.524	0.000	0.966	9
	SMEAN(RL_U2_BL)	0.871	1	0.871	4.095	0.045	0.520	23
	SMEAN(RL_U3_BL)	3.822	1	3.822	14.986	0.000	0.970	8
	SMEAN(RL_U4_BL)	4.649	1	4.649	23.224	0.000	0.998	3
	SMEAN(RL_U5_BL)	6.578	1	6.578	29.531	0.000	1.000	2
	SMEAN(RL_U6_BL)	4.874	1	4.874	18.028	0.000	0.988	5
	SMEAN(RL_U7_BL)	6.730	1	6.730	17.742	0.000	0.987	6
	SMEAN(RL_L1_MD)	0.361	1	0.361	3.832	0.052	0.494	24
	SMEAN(RL_L2_MD)	0.928	1	0.928	7.573	0.007	0.781	15
	SMEAN(RL_L3_MD)	5.194	1	5.194	45.459	0.000	1.000	1
	SMEAN(RL_L4_MD)	0.390	1	0.390	2.849	0.094	0.389	26
	SMEAN(RL_L5_MD)	1.013	1	1.013	6.153	0.014	0.693	18
	SMEAN(RL_L6_MD)	2.745	1	2.745	9.790	0.002	0.875	13
	SMEAN(RL_L7_MD)	2.019	1	2.019	10.573	0.001	0.898	12
	SMEAN(RL_L1_BL)	0.794	1	0.794	4.796	0.030	0.585	22
	SMEAN(RL_L2_BL)	0.206	1	0.206	1.355	0.246	0.212	27
	SMEAN(RL_L3_BL)	1.159	1	1.159	5.750	0.018	0.664	19
	SMEAN(RL_L4_BL)	0.663	1	0.663	3.437	0.066	0.453	25
	SMEAN(RL_L5_BL)	1.670	1	1.670	7.091	0.009	0.754	16
	SMEAN(RL_L6_BL)	3.024	1	3.024	14.176	0.000	0.963	10
	SMEAN(RL_L7_BL)	3.864	1	3.864	15.501	0.000	0.975	7

Table 5.13 Classification accuracy for sex prediction in Indians

				Predicted Group Membership		Total
			Sex	Females	Males	
Cases Selected	Original	Count	Females	58	20	78
			Males	18	55	73
		%	Females	74.4	25.6	100.0
			Males	24.7	75.3	100.0
	Cross-validated	Count	Females	56	22	78
			Males	18	55	73
		%	Females	71.8	28.2	100.0
			Males	24.7	75.3	100.0
Cases Not Selected	Original	Count	Females	13	4	17
			Males	5	12	17
		%	Females	76.5	23.5	100.0
			Males	29.4	70.6	100.0

74.8% of selected original grouped cases correctly classified.
73.5% of unselected original grouped cases correctly classified.
73.5% of selected cross-validated grouped cases correctly classified.

Table 5.14 List of discriminant function in Indians

Input	Variables	Coefficients[1]	Contrasts	Hit Ratio (%)			Validation: Proportion Chance Criterion			Validation: Press's Q			Cutting score
				Original	Test	L-O-O	Original	Test	L-O-O	Original	Test	L-O-O	
	UI1 MD	2.533	-21.969	64.2	70.6	64.2	B	B	B	S	S	S	0.010
	UI2 MD	2.01	-13.987	58.3	73.5	58.3	B	B	B	S	S	S	-0.003
	UC MD	2.573	-20.074	68.2	67.6	68.2	B	B	B	S	S	S	0.013
	UP1 MD	2.892	-20.875	60.9	58.8	60.9	B	B	B	S	NS	S	0.006
	UP2 MD	3.076	-21.105	61.6	61.8	61.6	B	B	B	S	NS	S	0.008
	UMI MD	1.93	-20.19	58.3	70.6	58.3	B	B	B	S	S	S	0.007
	UM2 MD	1.782	-18.079	70.2	73.5	69.5	B	B	B	S	S	S	0.008
	UI1 BL	2.143	-15.469	62.9	70.6	62.9	B	B	B	S	S	S	0.011
	UI2 BL	2.169	-14.148	64.2	73.5	64.2	B	B	B	S	S	S	0.006
	UC BL	1.98	-15.749	66.9	64.7	66.9	B	B	B	S	NS	S	0.011
	UP1 BL	2.235	-21.25	66.9	70.6	66.9	B	B	B	S	S	S	0.013
	UP2 BL	2.119	-19.926	68.9	61.8	67.5	B	B	B	S	NS	S	0.015
	UM1 BL	1.923	-21.837	67.5	79.4	66.2	B	B	B	S	S	S	0.012
	UM2 BL	1.624	-17.792	67.5	76.5	67.5	B	B	B	S	S	S	0.011
	LI1 MD	3.254	-17.839	54.3	73.5	54.3	B	B	B	NS	S	NS	0.006
	LI2 MD	2.857	-17.11	62.3	67.6	62.3	B	B	B	S	S	S	0.007
	LC MD	2.958	-20.12	73.5	73.5	73.5	B	B	B	S	S	S	0.018
	LP1 MD	2.701	-19.566	52.3	58.8	52.3	B	B	B	NS	NS	NS	0.004
	LP2 MD	2.465	-17.988	59.6	58.8	58.9	B	B	B	S	NS	S	0.007
	LM1 MD	1.888	-21.138	63.6	64.7	63.6	B	B	B	S	NS	S	0.009
	LM2 MD	2.289	-23.808	75.5	91.2	75.5	B	B	B	S	S	S	0.009
	LI1 BL	2.459	-14.644	62.3	73.5	62.3	B	B	B	S	S	S	0.006
	LI2 BL	2.564	-15.932	58.9	70.6	58.9	B	B	B	S	S	S	0.003
	LC BL	2.227	-15.867	66.2	64.7	66.2	B	B	B	S	NS	S	0.007
	LP1 BL	2.276	-18.506	54.3	70.6	54.3	B	B	B	NS	S	NS	0.005

Table 5.14 (continued)

Input	Variables	Coefficients[1]	Contrasts	Hit Ratio (%)			Validation						Cutting score
							Proportion Chance Criterion			Press's Q			
				Original	Test	L-O-O	Original	Test	L-O-O	Original	Test	L-O-O	
	LP2 BL	2.061	-17.996	57	85.3	57	B	B	B	NS	S	NS	0.007
	LM1 BL	2.165	-23.431	62.9	76.5	62.9	B	B	B	S	S	S	0.011
	LM2 BL	2.003	-21.013	68.2	82.4	68.2	B	B	B	S	S	S	0.011
All maxilla MD	UC MD	2.573	-20.074	68.2	67.6	68.2	B	B	B	S	S	S	0.013
All mandible MD	LC MD	2.958	-20.12	73.5	73.5	73.5	B	B	B	S	S	S	0.018
All MD	LC MD	3.448	-16.984	75.5	73.5	74.8	B	B	B	S	S	S	0.020
	UI2 MD	-0.929											
All BL maxilla	U5 BL	2.119	-19.926	68.9	61.8	67.5	B	B	B	S	NS	S	0.015
All BL mandible	LM2 BL	2.003	-21.013	68.2	82.4	68.2	B	B	B	S	S	S	0.011
All BL	UP2 BL	2.119	-19.926	68.9	61.8	67.5	B	B	B	S	NS	S	0.015

[1], Canonical discriminant function coefficients (unstandardized); B, better than chance; N, not better; S, significant at 5%; NS, not significant at 5%

Table 5.15 Descriptive statistics for tooth size in Jahai

Tooth	Sex	N	Mean	Std. Deviation	Tooth	Sex	N	Mean	Std. Deviation
				Mesiodistal					
UI1	Females	29	8.29	0.50	LI1	Females	29	5.30	0.26
	Males	26	8.60	0.43		Males	26	5.45	0.25
	Total	55	8.43	0.49		Total	55	5.37	0.26
UI2	Females	29	6.64	0.48	LI2	Females	29	6.05	0.47
	Males	26	7.03	0.48		Males	26	6.19	0.40
	Total	55	6.83	0.52		Total	55	6.12	0.44
UC	Females	29	7.65	0.39	LC	Females	29	6.85	0.35
	Males	26	7.93	0.42		Males	26	7.28	0.46
	Total	55	7.78	0.42		Total	55	7.05	0.45
UP1	Females	29	7.21	0.39	LP1	Females	29	7.16	0.50
	Males	26	7.17	0.38		Males	26	7.10	0.36
	Total	55	7.19	0.38		Total	55	7.13	0.43
UP2	Females	29	6.86	0.33	LP2	Females	29	7.16	0.36
	Males	26	6.80	0.24		Males	26	7.03	0.31
	Total	55	6.83	0.29		Total	55	7.09	0.34
UM1	Females	29	10.28	0.42	LM1	Females	29	11.01	0.46
	Males	26	10.58	0.50		Males	26	11.35	0.43
	Total	55	10.42	0.48		Total	55	11.17	0.47
UM2	Females	29	9.80	0.47	LM2	Females	29	10.02	0.46
	Males	26	9.95	0.50		Males	26	9.93	0.54
	Total	55	9.87	0.49		Total	55	9.98	0.50

Table 5.16 Tests of between-subject effects in Jahai

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Observed Power	Rank of sexual dimorphism
Sex	SMEAN(RL_U1_MD)	1.281	1	1.281	5.862	0.019	0.662	6
	SMEAN(RL_U2_MD)	2.113	1	2.113	9.099	0.004	0.842	2
	SMEAN(RL_U3_MD)	1.089	1	1.089	6.698	0.012	0.719	4
	SMEAN(RL_U4_MD)	0.022	1	0.022	0.151	0.699	0.067	14
	SMEAN(RL_U5_MD)	0.047	1	0.047	0.554	0.460	0.113	11
	SMEAN(RL_U6_MD)	1.268	1	1.268	5.889	0.019	0.664	5
	SMEAN(RL_U7_MD)	0.296	1	0.296	1.257	0.267	0.196	10
	SMEAN(RL_L1_MD)	0.310	1	0.310	4.746	0.034	0.571	7
	SMEAN(RL_L2_MD)	0.271	1	0.271	1.419	0.239	0.216	9
	SMEAN(RL_L3_MD)	2.521	1	2.521	15.635	0.000	0.973	1
	SMEAN(RL_L4_MD)	0.046	1	0.046	0.242	0.625	0.077	13
	SMEAN(RL_L5_MD)	0.232	1	0.232	2.065	0.157	0.292	8
	SMEAN(RL_L6_MD)	1.518	1	1.518	7.662	0.008	0.776	3
	SMEAN(RL_L7_MD)	0.117	1	0.117	0.470	0.496	0.103	12

Table 5.17 Classification accuracy for sex prediction in Jahai

			Predicted Group Membership		Total
		Sex	Females	Males	
Original	Count	Females	25	4	29
		Males	5	21	26
	%	Females	86.2	13.8	100.0
		Males	19.2	80.8	100.0
Cross-validated	Count	Females	25	4	29
		Males	7	19	26
	%	Females	86.2	13.8	100.0
		Males	26.9	73.1	100.0

83.6% of original grouped cases correctly classified.
80.0% of cross-validated grouped cases correctly classified.

Table 5.18 List of discriminant function catalogue for Jahai

Input	Variables	Coefficients[1]	Contrasts	Hit Ratio (%)		Validation: Proportion Chance Criterion		Validation: Press's Q		Cutting score
				Original	L-O-O	Original	L-O-O	Original	L-O-O	
All MD	LC MD LM2 MD	3.184 -1.859	-3.903	83.6	80.0	B	B	S	S	0.042
All maxilla MD	UI2 MD	2.075	-14.169	69.1	69.1	B	B	S	S	0.023
All mandible MD	LC MD LM2 MD	3.184 -1.859	-3.903	83.6	80.0	B	B	S	S	0.042

[1], Canonical discriminant function coefficients (unstandardized); B, better than chance; N, not better; S, significant at 5%; NS, not significant at 5%

Table 5.19 Descriptive statistics for tooth size in pooled ethnic groups

Tooth	Sex	N	Mean	SD	Tooth	Sex	N	Mean	SD
				Mesiodistal					
UI1	Females	230	8.55	0.49	LI1	Females	230	5.45	0.32
	Males	223	8.80	0.43		Males	223	5.56	0.32
	Total	453	8.67	0.48		Total	453	5.50	0.33
UI2	Females	230	7.00	0.58	LI2	Females	230	6.01	0.35
	Males	223	7.16	0.55		Males	223	6.13	0.35
	Total	453	7.08	0.57		Total	453	6.07	0.35
UC	Females	230	7.84	0.46	LC	Females	230	6.76	0.37
	Males	223	8.21	0.46		Males	223	7.16	0.41
	Total	453	8.02	0.50		Total	453	6.96	0.44
UP1	Females	230	7.37	0.42	LP1	Females	230	7.27	0.40
	Males	223	7.52	0.43		Males	223	7.44	0.40
	Total	453	7.44	0.43		Total	453	7.35	0.41
UP2	Females	230	6.94	0.39	LP2	Females	230	7.27	0.43
	Males	223	7.09	0.44		Males	223	7.45	0.43
	Total	453	7.01	0.42		Total	453	7.36	0.44
UM1	Females	230	10.43	0.50	LM1	Females	230	11.21	0.51
	Males	223	10.64	0.50		Males	223	11.55	0.50
	Total	453	10.53	0.51		Total	453	11.38	0.53
UM2	Females	230	9.93	0.54	LM2	Females	230	10.24	0.49
	Males	223	10.25	0.49		Males	223	10.64	0.51
	Total	453	10.09	0.54		Total	453	10.44	0.54
				Buccolingual					
UI1	Females	230	7.10	0.46	LI1	Females	230	5.80	0.39
	Males	223	7.40	0.45		Males	223	6.00	0.33
	Total	453	7.25	0.48		Total	453	5.90	0.37
UI2	Females	230	6.48	0.47	LI2	Females	230	6.16	0.36
	Males	223	6.72	0.45		Males	223	6.28	0.38
	Total	453	6.60	0.48		Total	453	6.22	0.37
UC	Females	230	7.94	0.51	LC	Females	230	7.13	0.48
	Males	223	8.25	0.52		Males	223	7.40	0.53
	Total	453	8.09	0.54		Total	453	7.26	0.52
UP1	Females	230	9.46	0.46	LP1	Females	230	8.04	0.41
	Males	223	9.82	0.51		Males	223	8.32	0.48
	Total	453	9.64	0.52		Total	453	8.17	0.47
UP2	Females	230	9.31	0.53	LP2	Females	230	8.59	0.43
	Males	223	9.66	0.53		Males	223	8.86	0.48
	Total	453	9.48	0.56		Total	453	8.72	0.47
UM1	Females	230	11.18	0.52	LM1	Females	230	10.75	0.45
	Males	223	11.63	0.50		Males	223	11.03	0.46
	Total	453	11.40	0.56		Total	453	10.89	0.48
UM2	Females	230	10.95	0.61	LM2	Females	230	10.40	0.48
	Males	223	11.39	0.68		Males	223	10.78	0.50
	Total	453	11.16	0.68		Total	453	10.58	0.52

N, sample size; SD, standard deviation

Table 5.20 Tests of between-subject effects in pooled ethnic groups

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Observed Power	Rank of sexual dimorphism
Sex	SMEAN(RL_U1_MD)	7.334	1	7.334	34.559	0.000	1.000	17
	SMEAN(RL_U2_MD)	3.095	1	3.095	9.595	0.002	0.871	28
	SMEAN(RL_U3_MD)	15.485	1	15.485	72.161	0.000	1.000	4
	SMEAN(RL_U4_MD)	2.828	1	2.828	15.544	0.000	0.976	23
	SMEAN(RL_U5_MD)	2.516	1	2.516	14.702	0.000	0.969	25
	SMEAN(RL_U6_MD)	5.145	1	5.145	20.658	0.000	0.995	21
	SMEAN(RL_U7_MD)	11.409	1	11.409	42.872	0.000	1.000	12
	SMEAN(RL_U1_BL)	9.912	1	9.912	48.129	0.000	1.000	10
	SMEAN(RL_U2_BL)	6.327	1	6.327	29.516	0.000	1.000	19
	SMEAN(RL_U3_BL)	11.287	1	11.287	42.408	0.000	1.000	13
	SMEAN(RL_U4_BL)	14.883	1	14.883	63.031	0.000	1.000	6
	SMEAN(RL_U5_BL)	13.806	1	13.806	48.500	0.000	1.000	9
	SMEAN(RL_U6_BL)	22.702	1	22.702	86.468	0.000	1.000	2
	SMEAN(RL_U7_BL)	22.141	1	22.141	53.178	0.000	1.000	7
	SMEAN(RL_L1_MD)	1.533	1	1.533	14.802	0.000	0.970	24
	SMEAN(RL_L2_MD)	1.495	1	1.495	12.158	0.001	0.936	26
	SMEAN(RL_L3_MD)	18.776	1	18.776	122.079	0.000	1.000	1
	SMEAN(RL_L4_MD)	3.264	1	3.264	20.276	0.000	0.994	22
	SMEAN(RL_L5_MD)	3.864	1	3.864	20.764	0.000	0.995	20
	SMEAN(RL_L6_MD)	12.851	1	12.851	50.497	0.000	1.000	8
	SMEAN(RL_L7_MD)	18.097	1	18.097	73.269	0.000	1.000	3
	SMEAN(RL_L1_BL)	4.647	1	4.647	35.794	0.000	1.000	16
	SMEAN(RL_L2_BL)	1.558	1	1.558	11.416	0.001	0.921	27
	SMEAN(RL_L3_BL)	8.496	1	8.496	33.391	0.000	1.000	18
	SMEAN(RL_L4_BL)	8.892	1	8.892	44.136	0.000	1.000	11
	SMEAN(RL_L5_BL)	7.859	1	7.859	37.911	0.000	1.000	15
	SMEAN(RL_L6_BL)	8.773	1	8.773	42.207	0.000	1.000	14
	SMEAN(RL_L7_BL)	16.728	1	16.728	70.075	0.000	1.000	5

Table 5.21 Classification accuracy in pooled ethnic groups

				Predicted Group Membership		Total
			Sex	Females	Males	
Cases Selected	Original	Count	Females	188	42	230
			Males	61	162	223
		%	Females	81.7	18.3	100.0
			Males	27.4	72.6	100.0
	Cross-validated	Count	Females	184	46	230
			Males	64	159	223
		%	Females	80.0	20.0	100.0
			Males	28.7	71.3	100.0
Cases Not Selected	Original	Count	Females	47	5	52
			Males	13	34	47
		%	Females	90.4	9.6	100.0
			Males	27.7	72.3	100.0

Cross validation is done only for those cases in the analysis. In cross validation, each case is classified by the functions derived from all cases other than that case.

77.3% of selected original grouped cases correctly classified.

81.8% of unselected original grouped cases correctly classified.

75.7% of selected cross-validated grouped cases correctly classified.

Table 5.22 Classification accuracy for sex prediction in three ethnic groups

Malays		Predicted group membership		
		Males	Females	Total
original	Males	53	22	75
	Females	12	71	83
test	Males	12	4	16
	Females	2	14	16
% original	Males	70.7	29.3	100%
	Females	14.5	85.5	100%
% test	Males	75.0	25.0	100%
	Females	12.5	87.5	100%

a. 78.1% of selected original grouped correctly classified
b. 81.3% of test sample grouped correctly classified

Chinese		Predicted group membership		
		Males	Females	Total
original	Males	57	18	75
	Females	15	54	69
test	Males	11	3	14
	Females	1	18	19
% original	Males	76	24	100%
	Females	21.7	78.3	100%
% test	Males	78.6	21.4	100%
	Females	5.3	94.7	100%

a. 77.1% of selected original grouped correctly classified
b. 86.7% of test sample grouped correctly classified

Indians		Predicted group membership		
		Males	Females	Total
original	Males	52	21	73
	Females	15	63	78
test	Males	11	6	17
	Females	2	15	17
% original	Males	71.2	28.8	100%
	Females	19.2	80.8	100%
% test	Males	64.7	35.3	100%
	Females	11.8	88.2	100%

a. 76.0% of selected original grouped correctly classified
b. 76.5% of test sample grouped correctly classified

Table 5.23 List of discriminant function in pooled ethnic groups

Input	Variables	Coefficients	Contrasts	Hit ratio (%)			Validation						Cutting score
							Proportion chance criterion			Press's Q			
				Original	Test	L-O-O	Original	Test	L-O-O	Original	Test	L-O-O	
All maxilla MD	UC MD	1.901	-20.394	68.7	75.8	68	B	B	B	S	S	S	0.007
	UM2 MD	-0.792											
	UP2 MD	1.061											
All mandible MD	LI2 MD	-1.019	-18.54	74.2	79.8	74	B	B	B	S	S	S	0.01
	LC MD	2.688											
	LP1 MD	-0.816											
	LM2 MD	1.152											
All maxilla BL	UI1 BL	0.643	-24.551	68	67.7	67.3	B	B	B	S	S	S	0.0075
	UP1 BL	0.659											
	UM1 BL	1.187											
All mandible BL	LI1 BL	1.422	-22.648	68.4	73.7	68	B	B	B	S	S	S	0.007
	LI2 BL	-1.176											
	LP1 BL	0.801											
	LM2 BL	1.421											
All except incisors	UP1 MD	-1.236	-22.687	75.5	84.8	74.8	B	B	B	S	S	S	0.011
	UP2 MD	-0.657											
	UP1 BL	0.65											
	UM1 BL	0.506											
	LC MD	2.704											
	LM2 MD	0.961											

5.4. *Discussion*

Analyses in this chapter used the same tooth size data as in Chapter 4. After noting missing values in the previous data, mean values were used to replace missing values to maintain sample size for the multivariate analyses (Chiu and Donlon, 2000). This strategy seemed to work in that for every group, the majority of predictors had high power to detect sex differences if true differences existed. The effect of sample size on the power of the study was illustrated in the Jahai and pooled ethnic groups. Even though sex prediction performance in the Jahai was comparable with other groups, the power for each predictor was generally lower whereas the majority of predictors in the pooled ethnic groups obtained 100% power.

Cases that had been identified as outliers were examined individually in the predicted membership column in SPSS data view. Only one case, case number 164, was misclassified as male. Therefore, the hit ratio results were unaffected by outlier effects.

The pattern of sexual dimorphism based on F-values gave comparable results to the sexual dimorphism formula of Garn *et al.* (1964). Except for Chinese, the mesiodistal diameter of lower canine was highlighted as the most dimorphic dimension. However, in Chinese the lower second molar was the most dimorphic tooth. There were, however, some variations in which tooth showing the least sexual dimorphism. All dimensions identified as least dimorphic were mesiodistal diameters: the upper second premolar in Malays, the lower lateral incisor in Chinese, and the upper lateral incisor in India. In Jahai, for whom only mesiodistal diameters were used as an input, the upper first premolar was found to be the least dimorphic.

When compared with the univariate analysis of sexual dimorphism, only the first ranked variable remained as a strong predictor in the discriminant functions after stepwise procedures. The rest of the strong predictors in the univariate rankings were not necessarily selected as strong discriminative variables in the discriminant function analyses. Hair *et al.* (1995) explained this from a statistical point of view by stating that collinearity with the predictor already in the function may not allow the next predictors to be included in the function even though their univariate F-value may indicate strong sex dimorphism. In essence, univariate assessment of sexual dimorphism is not sufficient to predict a combination of predictors for sexual dimorphism studies. The present study supports the findings of Potter (1972), Kieser *et al.* (1985) and Kieser (1990) who compared univariate and multivariate analyses for sexual dimorphism studies.

Results from hit ratio values were comparable with other published material in different populations (Ditch and Rose, 1972; Sciulli *et al.*, 1977; Brown and Townsend, 1979; Haeussler

et al., 1989; Iscan and Kedici, 2003). For functions obtained from 28 input variables, the hit ratios in original, L-O-O procedure and test sample were more stable in the stepwise procedure than hit ratios for functions obtained from single or selected variables. As an example, one of the functions in the Indians (Table 5.14) consisted of a single predictor, LM2MD, the hit ratio in the test sample (91.2%) was much higher than the hit ratio in the original and L-O-O samples (75.5%). The same trend could be observed in Malays and Chinese.

Comparing hit ratio performance between the three groups; the Chinese sample was the most dimorphic and had more functions that were suitable for sex prediction. This reflects the pattern of sexual dimorphism in univariate analyses of Chinese where the majority of predictor variables were significant at 5%.

Since this study aimed to explore sex prediction models, both statistical and practical approaches were tested. There were two important findings which indicated the usefulness of odontometry for sex predictions in forensic and archaeological situations. The first important finding was that for each ethnic group, several functions reached an accuracy better than chance using only a single predictor variable. Of course, in a real forensic situation, there is no guarantee that the investigators would be able to collect a complete set of teeth for analysis. Therefore, in restricted circumstances, the size of a single tooth could provide reasonably accurate sex prediction (as shown in Tables 5.6, 5.10, 5.14, 5.18 and 5.23). The second important finding is the development of a non-ethnic specific sex prediction model which would enable sex prediction without knowing ancestry. From separate analyses, as shown in Tables 5.21, 5.22 and 5.23, a prediction model generated using pooled tooth size measurements from Malays, Chinese and Indian provides comparable accuracy to the ethnic specific prediction models. Despite the advantage of non-ethnic specific models, a limitation is that sex variation in other minority groups who live on the Malaysian Peninsula is still to be explored. These models, however, have proven to be reasonably accurate for use in three Malaysian major groups; Malays, Chinese and Indian.

As with other methods used for sex prediction, the quality and quantity of evidence available for analysis is crucial in forensic situations. Limitations will include any post-eruptive changes such as caries, wear and restorations which could compromise the use of particular predictor variables. However, the present study provides strong support for the role of odontometry as an alternative scientific method for sex prediction in forensic and anthropological situations.

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Chapter 6 Odontometric profiles for human identification in Malaysian populations

6.1 Introduction

Recent terrorist attacks in Bali and Southern Thailand, and natural disasters in South East Asia, including the tsunami that hit Aceh Indonesia, Phuket and coastal mainland Thailand and some parts of the west coast of Peninsula Malaysia, and the earthquake in Pakistan and Kashmir, have left investigators with thousands of unnamed bodies requiring identification. Unidentified bodies lead to problems in settling benefits (e.g. insurance) for the affected families and in many societies mean that the legal procedures following death cannot be commenced. Descriptions of different scientific identification methods have been provided in Chapter 1, together with their respective advantages and disadvantages.

In some instances, like in the tsunami disaster, there is no indication as to who has been involved (referred to as an open disaster). Where isolated bodies are found in homicide cases, the investigators need a clue(s) for comparative identification to take place. The beginning of investigations for identification requires important information relating to the time of death or disappearance, ancestry (ethnicity), age at the time of death, sex and height. Other corroborative information such as personal belongings, profession, birth marks, scar tissue after surgery or implants may also benefit the investigation. The above process is described as reconstructive identification analysis.

Odontometry profiles have been used to characterize population affinities and assist in reconstruction of histories (Hanihara, 1976; Hanihara and Ueda, 1979; Kieser *et al.*, 1985; Kieser, 1990; Hanihara, 1998; Matsumura and Majid, 1999; Hanihara and Ishida, 2005; Matsumura and Hudson, 2005). Despite many publications showing the successful use of odontometric data for establishment of inter-population relationships, only a few publications have reported their use to predict ethnicity (Matis and Zwemer, 1971; Haeussler *et al.*, 1989; Chiu and Donlon, 2000). Matis and Zwemer (1971) used combined odontometry and non-metric data in discriminant analyses to predict ancestry between American Indians (Pima, Navajo, Apache and Papago) and Alaskan Eskimos. Their results reflected the genetic distance between the population groups and showed a high hit ratio (97%) for comparisons between the two groups, but less sensitive discrimination between different tribes within the American Indian groups. Haeussler *et al.* (1989) found an 82% success rate in discriminating San from Central Sotho using pooled sex data, an 81% success rate using male data and 91%

using female data. They suggested that sexual dimorphism did not influence ethnic classification results. Chiu and Donlon (2000) found a high hit ratio from discriminant function analysis (93.9%) in discriminating between Caucasoids and Mongoloids from Sydney, Australia. Recent research by Hanihara and Ishida (2005) suggested metric analyses were useful in analyzing population relationships as long as the level of differentiation was not less than tribal level. In a way, the findings from distance analyses and discriminant analyses show some similarity in their pattern of relationships. The further the genetic distance, the better one can expect the hit ratio to be from discriminant function analyses.

In Chapter 4, multivariate analyses indicated that the Malays and Chinese were closer to each other than Indians. Taking into account the results from the studies of Matis and Zwemer (1971) and Hanihara and Ishida (2005), the possibility will now be explored of combining Malays and Chinese to represent a Mongoloid group in a discriminant function analysis.

Currently, there has been no similar study attempted for Malaysian populations. Therefore, in this chapter the combination of predictor variables is explored which will best discriminate ethnicity and sex, after interaction effects, and enable discriminant functions to be generated for practical forensic applications.

6.2 Materials and methods

Initially the same samples (Table 6.1) used in Chapter 5 were utilized in a general linear modeling (GLM) multivariate analysis of variance (MANOVA). Missing values were replaced with group means resulting in complete sets of tooth size data for all variables. The MANOVA used the 28 tooth sizes as dependent variables, and ethnicity (three levels of treatment) and sex (two levels of treatment) as independent variables, resulting in 3x2 factorial designs. The MANOVA analysis was used to evaluate the main and interaction effects of ethnicity and sex on tooth size. If the interaction effects were significant, then ethnicity prediction would be influenced by the amount of sexual dimorphism in tooth size. In these cases, analyses of ethnicity prediction should be made for males and females separately. Statistical tests of the underlying assumptions for MANOVA and discriminant function analyses reported in Chapter 5 indicated that the data were acceptable for analysis.

Ethnic prediction models were explored using discriminant function analysis for males, females and sexes pooled (mimicking the situation of unknown sex). External validation of the hit ratio using a test sample that was not part of the data used to generate linear discriminant functions was employed. The hit ratio was also internally validated using the leave-one-out (LOO) procedure which means each case in the analysis was classified by the functions derived from all cases other than that case (n-1) (Hair *et al.*, 1995). 99 cases were used for external validation. Details had been given in Chapter 5.

Pillai's Trace was used to assess multivariate significance of the main and interaction effects of ethnicity and sex collectively across 28 variables in the general linear modeling. The rest of the procedures used in the MANOVA and discriminant functions were as described in Chapter 5. Two linear discriminant functions were generated from the analysis using three categorical groups (Malays, Chinese and Indians). Group prediction membership utilized a territorial map. The territorial map showed three ethnic group boundaries of distributions of discriminant scores. Each case had two discriminant scores derived from calculation of two discriminant functions. In the territorial map, each case was located according to its coordinate (x,y). The x-value was the discriminant score derived from Function 1 while y-value was the discriminant score from Function 2.

A second analysis used a combination of Malays and Chinese to form a Mongoloid group (Table 6.2), as well as the original Indian sample. The sample was randomly double-stratified, selected from the list of Malays and Chinese in Table 6.1. The total sample for each group was set equal to the size of the male Indian group, that is 73 (Table 6.2). The test

sample for the discriminant function test was also randomly selected so that 34 cases were left for both the Indian and Mongoloid groups. Normality testing shown in Appendices 6.1, 6.2, 6.3, and 6.4 indicated that only one variable in the male Indian sample was significantly skewed and some variables were significantly kurtotic. Z-scores were calculated to assess outliers. Both multivariate analyses, MANOVA and DFA were conducted using this sample for sex and ethnicity prediction in the same manner as described above. Group differences between tooth sizes in Mongoloids and Indians were calculated from general linear modeling. Direct interpretations at $p<0.05$ are acceptable with GLM as it has controlled Type 1 error (Bonferroni's correction is not required). The decision for group membership was based on the cutting score, derived from the average of group centroids. The results of sex prediction were compared with those of sex prediction for Malays and Chinese given in Chapter 5.

Internal and external validations for every hit ratio in this study were assessed using proportion chance criterion and Press's Q statistics. The proportional chance criterion (Cpro) is measured by squaring the proportions of each group sample size; $Cpro = p^2_1 + p^2_2 + p^2_3$. The discriminant models were considered to be valid if the hit ratio exceeded Cpro. The statistical significance of the hit ratio was tested using Press's Q statistics for original and test samples. If Press's Q exceeded the critical value of 3.84 (5% significance level), the discriminant analysis was considered to be better than chance in predicting group membership. The formula for Press's Q is as follows:

$$\text{Press's Q} = \frac{(N-(n*K))^2}{N(K-1)}$$

N = total sample size

n = number of observations correctly classified

K = number of groups

Table 6.1 Sample distributions according to ethnicity and sex

Ethnic	Sex	N
Malays	Females	83
	Males	75
	Total	158
Chinese	Females	69
	Males	75
	Total	144
Indians	Females	78
	Males	73
	Total	151
Total	Females	230
	Males	223
	Total	453

Table 6.2 Sample distributions for Mongoloids and Indians

Ethnic	Sex	N
Malays	Females	37
	Males	36
	Total	73
Chinese	Females	36
	Males	37
	Total	73
Indians	Females	73
	Males	73
	Total	146
Total	Females	146
	Males	146
	Total	292

6.3 Results

Data were considered acceptable for further multivariate analyses and none of the data exceeded a z-score of 4.0. The sample sizes met the minimum requirements for MANOVA and discriminant function analyses. Details of the minimum requirements are as given in Chapter 5.

Results are presented under two headings, comparison between three ethnic groups and Mongoloids versus Indians.

6.3.1 Comparison of three ethnic groups

These are the results for the first stage analysis. Table 6.3 shows the main and interaction effects of sex and ethnicity from multivariate analysis. The interaction was found to be highly significant as well as main effects for ethnicity and sex. The power for significance testing was 100%.

Table 6.4 shows the summary of canonical discriminant functions for ethnicity predictions in the case of known male samples. Two discriminant functions were found to be significant ($p<0.05$) with a chi-square analysis but they contributed only 16% and 36% to the observed variation. Table 6.5 lists the unstandardized discriminant function coefficients for each of the nine predictors selected as best ethnicity predictors. The territorial map shows the group centroids and the boundaries for reference of group membership prediction (Figure 6.1). Table 6.6 shows the average hit ratio for ethnic group prediction. The success rate ranged from 49% to 65% and all hit ratios were better than chance based on calculation of proportion chance criterion, Cpro (33.3%) and Press's Q statistics (for original 100.8; for test sample 5.14). Figure 6.2 illustrates the overlapping relationship of the distributions of male cases in the three ethnic groups. Function 1 separated Indians from Malays and Chinese, but Function 2 equivocally separated the groups.

Appendix 6.5 shows the discriminant function summary for ethnic group prediction using female samples. The discriminant functions attributed 11%-31% to the total variance observed. The functions were significant at $p<0.05$ as tested by a chi-square analysis and the functions consisted of eight predictors (Appendix 6.6). The territorial map provided group boundaries as reference for group membership predictions (Figure 6.3). Table 6.7 shows the average of the hit ratios which ranged from 50% to 58.7%. Based on Cpro (33.5%) and Press's Q statistics (for original 65.6 and test sample 6.5), all hit ratios were better than chance. Figure 6.4 shows the relationships and distributions of female cases in the three ethnic groups were similar to findings in males.

Appendix 6.7 shows that discriminant functions derived from pooled-sex samples were significant at $p<0.05$ and accounted for 12%-36% of the observed variation. Twelve predictors were selected for two linear discriminant functions for ethnic group prediction and unstandardized coefficients were listed for each variable (Appendix 6.8). Discriminant scores from these functions were compared with a territorial map for ethnic group membership predictions (Figure 6.5). Average hit ratios ranged from 52% to 62% and were better than chance (Table 6.8). The Cpro (33.4%) and Press's Q (for original 162.8 and for test sample 14.7) statistics confirmed these results. Figure 6.6 shows ethnic group relationships and overlapping distributions consistent with high case misclassifications.

6.3.2 Mongoloids versus Indians

Table 6.9 indicates that the dentition in Mongoloids was larger than Indians for 16 variables at $p<0.05$. None of the tooth size variables in Indians were larger than those in Mongoloids. Table 6.10 shows main and interaction effects of sex and ethnicity from general linear modeling procedures. The main effects of sex and ethnicity were significant at $p<0.05$. The interaction between sex and ethnicity was associated with a probability level of 0.10. The alpha level was adjusted to accommodate the lack of power of the study.

Table 6.11 shows that stepwise procedures selected seven predictors as the best sex discriminators using combined Mongoloid and Indian tooth size data. The discriminant function generated from these predictors was significant at $p<0.05$ using a chi-square analysis and accounted for 31% of the total observed variation (Appendix 6.9). Appendix 6.10 lists the unstandardized coefficients of the discriminant function for each predictor. The cutting score was zero, derived from the average of group centroids. Cases with discriminant scores larger than zero were classified as male. Table 6.12 shows the average hit ratio of sex prediction ranged from 75.7% to 76.5%, without any obvious difference between the original, test and LOO samples. All hit ratios were better than chance based on Cpro (50%) and Press's Q statistics (for the original 81.2 and for the test sample 19.1).

Table 6.13 shows the five predictors selected as best discriminators in Mongoloids. The discriminant function formed from these predictors was significant at $p<0.05$ and accounted for 29% of the total observed variation (Appendix 6.11). Appendix 6.12 shows the list of unstandardized discriminant function coefficients that were used in generating the linear discriminant function. Discriminant scores larger than the cutting score, 0, were classified as male. The hit ratio ranged from 70.0% to 82.4% and all were better than chance, based on

Cpro (50%) and Press's Q statistics (for the original 24.7 and for the test sample 14.2) (Table 6.14).

Table 6.15 shows the six predictors selected as best ethnic group discriminators in male Mongoloids and Indians. The discriminant function formed from six predictors was significant at $p<0.05$, using a chi-square analysis and is shown in Appendix 6.13. The function accounted for 36% of total variation. Appendix 6.14 shows the list of discriminant functions coefficients for each predictor. Discriminant scores larger than the cutting score, 0, were placed as Mongoloid. Table 6.16 shows high hit ratios classifying Mongoloid and Indian males, ranging from 75.3% to 80.1%. The hit ratio was better than chance based on calculation of Cpro (50%) and Press's Q statistic (for the original 53.0 and for the test sample 9.53).

Table 6.17 shows the six predictors that significantly contributed to discrimination between Mongoloids and Indians using female data only. This discriminant function was found to account for 36% of the total observed variation and was significant as tested by a chi-square analysis (Appendix 6.15). Appendix 6.16 shows the list of coefficients and the cutting score which was zero. Table 6.18 indicates that the range of hit ratios was from 64.7% to 78.8% and hit ratio in the original sample and LOO procedure were better than chance. The only exception was for the hit ratio in the test sample based on the Press's Q statistics. The calculated values from the hit ratio classification matrix were 48.3 for the original samples and 2.94 for test sample.

Table 6.19 shows the eight predictors that best discriminated Mongoloids and Indians, using data from both sexes. Appendix 6.17 shows that the function formed by these eight predictors was significant and accounted for 36% of the total variation. The coefficients of the discriminant function are given for each predictor in Appendix 6.18 and the cutting score was zero. The hit ratio was found to range from 67.6% in the test sample to 75% in the original and LOO procedure. All hit ratios were better than chance based on Cpro (50%) and Press's Q (for the original 83.3 and for the test sample 8.47) (Table 6.20).

Figure 6.4 provides a graphical presentation of individual discriminant scores for pooled sex data (input of 28 variables), indicating the Mongoloid group had a larger discriminant score than the Indian sample with the cutting score set at 0. This graph also shows misclassified ethnicity for several individuals in both groups.

Table 6.21 shows four variations of input that indicate only one function, all mesiodistal diameters in the maxillary teeth, obtained a hit ratio of more than 70% and performed better than chance in both validation tests. Examples of using the function in practice are given in Appendix 6.19.

Table 6.3 General linear modeling multivariate analysis of variance for three ethnic groups

Effect		Value	F	Hypothesis df	Error df	Sig.	Observed Power[a]
Sex	Pillai's Trace	0.402	10.07	28	420	0.0000	1.000
	Wilks' Lambda	0.598	10.07	28	420	0.0000	1.000
	Hotelling's Trace	0.672	10.07	28	420	0.0000	1.000
	Roy's Largest Root	0.672	10.07	28	420	0.0000	1.000
Ethnicity	Pillai's Trace	0.552	5.74	56	842	0.0000	1.000
	Wilks' Lambda	0.509	6.01	56	840	0.0000	1.000
	Hotelling's Trace	0.841	6.29	56	838	0.0000	1.000
	Roy's Largest Root	0.656	9.86	28	421	0.0000	1.000
Sex*Ethnicity	Pillai's Trace	0.189	1.57	56	842	0.0059	1.000
	Wilks' Lambda	0.820	1.56	56	840	0.0061	1.000
	Hotelling's Trace	0.209	1.56	56	838	0.0063	1.000
	Roy's Largest Root	0.114	1.72	28	421	0.0138	0.992

a, Computed using alpha = .05

Table 6.4 Canonical discriminant function summary in males (three ethnic groups)

Test of Function(s)	Wilks' Lambda	Chi-square	df	Sig.
1 through 2	0.5379	133.94	18	0.000
2	0.8327	39.54	8	0.000

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	0.5481	73.2	73.2	0.595
2	0.2009	26.8	100.0	0.409

First 2 canonical discriminant functions were used in the analysis.

Table 6.5 Canonical discriminant function coefficients and group centroids in males (three ethnic groups)

Canonical Discriminant Function Coefficients

	Function	
	1	2
SMEAN(RL_U1_MD)	-1.2121	1.2035
SMEAN(RL_U4_MD)	2.4918	0.8387
SMEAN(RL_U5_MD)	0.7652	1.3161
SMEAN(RL_U6_MD)	-0.3363	-1.2420
SMEAN(RL_U7_MD)	-0.9449	0.3761
SMEAN(RL_L5_MD)	-1.3520	0.0317
SMEAN(RL_L6_MD)	1.5389	-1.0483
SMEAN(RL_L3_BL)	0.6719	-0.8498
SMEAN(RL_L6_BL)	-0.5119	1.0337
(Constant)	-7.2583	-10.1178

Unstandardized coefficients

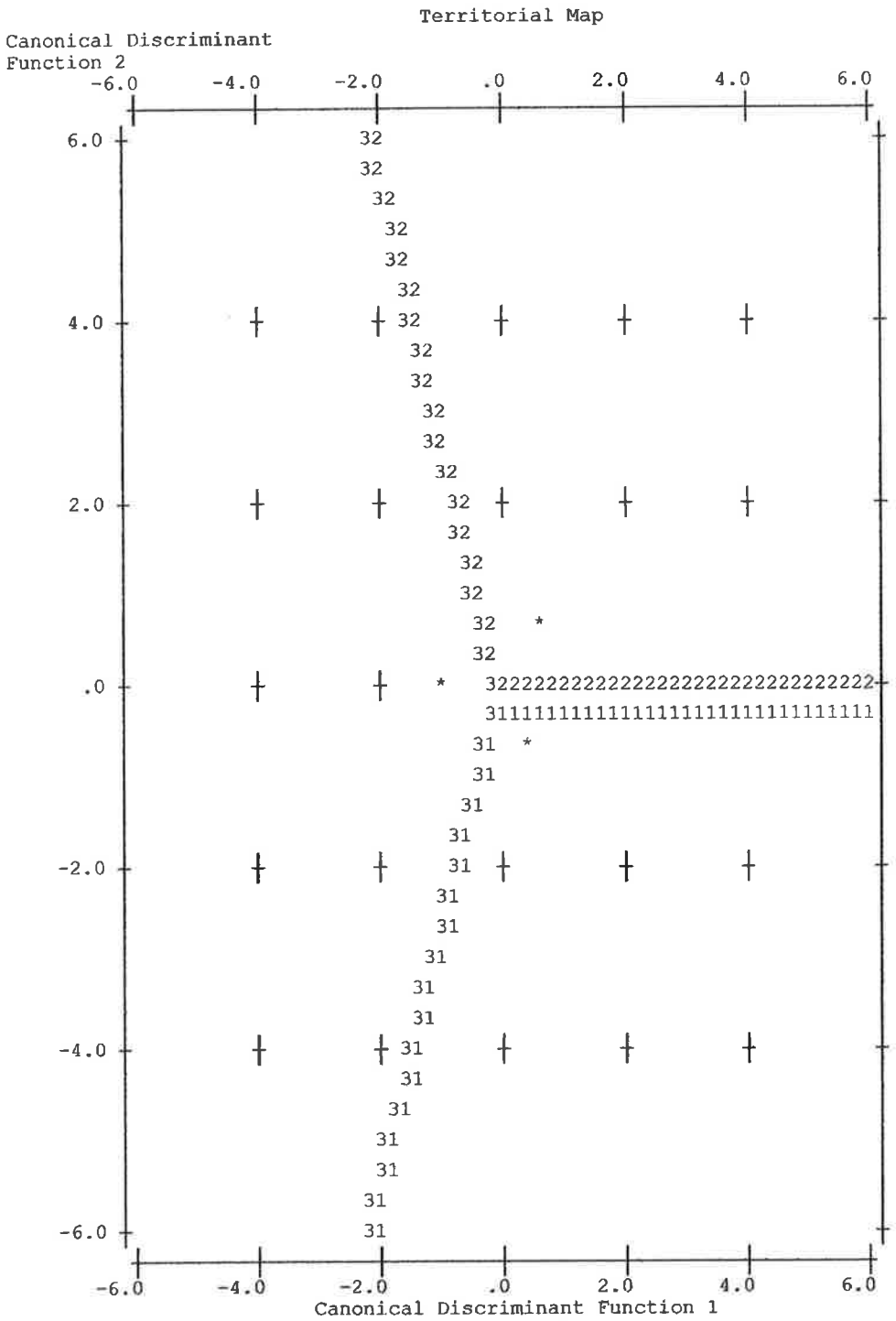
Functions at Group Centroids

	Function	
ETHNIC	1	2
Malays	0.497	-0.548
Chinese	0.529	0.537
Indians	-1.054	0.011

Unstandardized canonical discriminant functions evaluated at group means

Refer to Chapter 5 for abbreviation used.

Figure 6.1 Territorial map for prediction of ethnicity using male data (three ethnic groups)



Symbols used in territorial map

Symbol	Group	Label
1	1	Malays
2	2	Chinese
3	3	Indians
*	Indicates a group centroid	

Table 6.6 Hit ratio for prediction of ethnicity using male data (three ethnic groups)

				Predicted Group Membership			Total
			Ethnicity	Malays	Chinese	Indians	
Cases Selected	Original	Count	Malays	43	23	9	75
			Chinese	18	46	11	75
			Indians	9	8	56	73
		%	Malays	57.3	30.7	12.0	100.0
			Chinese	24.0	61.3	14.7	100.0
			Indians	12.3	11.0	76.7	100.0
	Cross-validated	Count	Malays	39	26	10	75
			Chinese	21	43	11	75
			Indians	11	9	53	73
		%	Malays	52.0	34.7	13.3	100.0
			Chinese	28.0	57.3	14.7	100.0
			Indians	15.1	12.3	72.6	100.0
Cases Not Selected	Original	Count	Malays	6	6	4	16
			Chinese	5	8	1	14
			Indians	5	3	9	17
		%	Malays	37.5	37.5	25.0	100.0
			Chinese	35.7	57.1	7.1	100.0
			Indians	29.4	17.6	52.9	100.0

65.0% of selected original grouped cases correctly classified.
48.9% of unselected original grouped cases correctly classified.
60.5% of selected cross-validated grouped cases correctly classified.

Figure 6.2 Canonical discriminant functions for prediction of ethnicity using male data (three ethnic groups)

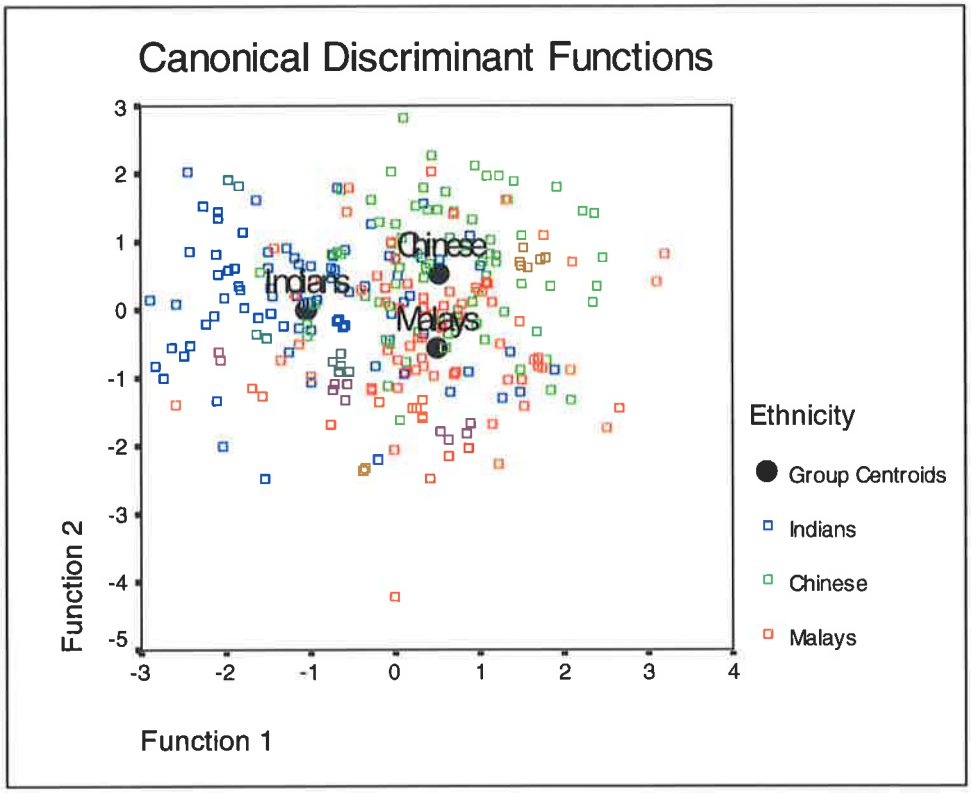
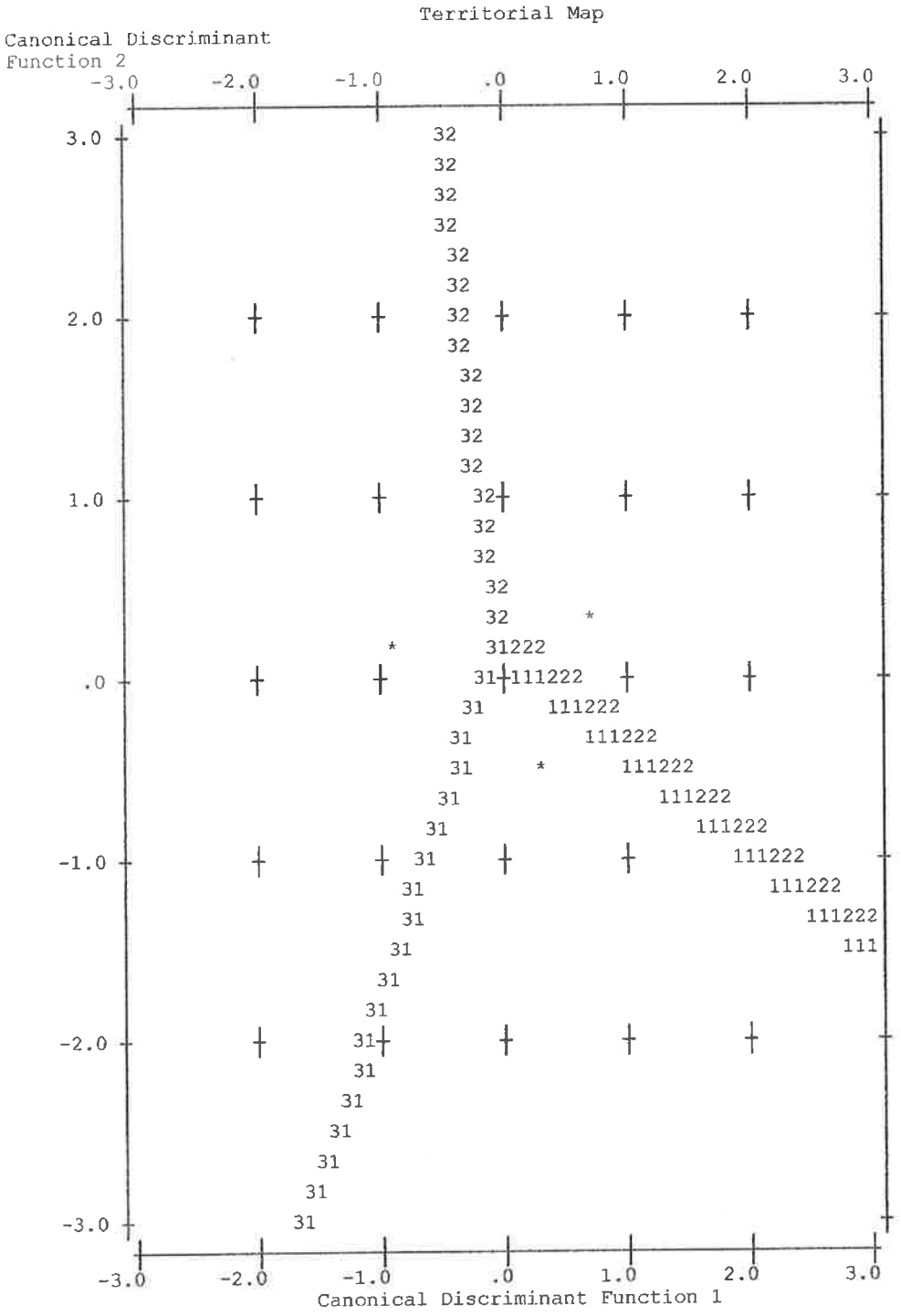


Figure 6.3 Territorial map for prediction of ethnicity using female data (three ethnic groups)



Symbols used in territorial map

Symbol	Group	Label
1	1	Malays
2	2	Chinese
3	3	Indians
*	Indicates a group centroid	

Table 6.7 Hit ratio for prediction of ethnicity using female data (three ethnic groups)

				Predicted Group Membership			Total
			Ethnicity	Malays	Chinese	Indians	
Cases Selected	Original	Count	Malays	41	26	16	83
			Chinese	16	40	13	69
			Indians	17	7	54	78
		%	Malays	49.4	31.3	19.3	100.0
			Chinese	23.2	58.0	18.8	100.0
			Indians	21.8	9.0	69.2	100.0
	Cross-validated	Count	Malays	37	29	17	83
			Chinese	20	36	13	69
			Indians	19	7	52	78
		%	Malays	44.6	34.9	20.5	100.0
			Chinese	29.0	52.2	18.8	100.0
			Indians	24.4	9.0	66.7	100.0
Cases Not Selected	Original	Count	Malays	6	7	3	16
			Chinese	6	10	3	19
			Indians	2	5	10	17
		%	Malays	37.5	43.8	18.8	100.0
			Chinese	31.6	52.6	15.8	100.0
			Indians	11.8	29.4	58.8	100.0

58.7% of selected original grouped cases correctly classified.
50.0% of unselected original grouped cases correctly classified.
54.3% of selected cross-validated grouped cases correctly classified.

Figure 6.4 Canonical discriminant functions for prediction of ethnicity using female data (three ethnic groups)

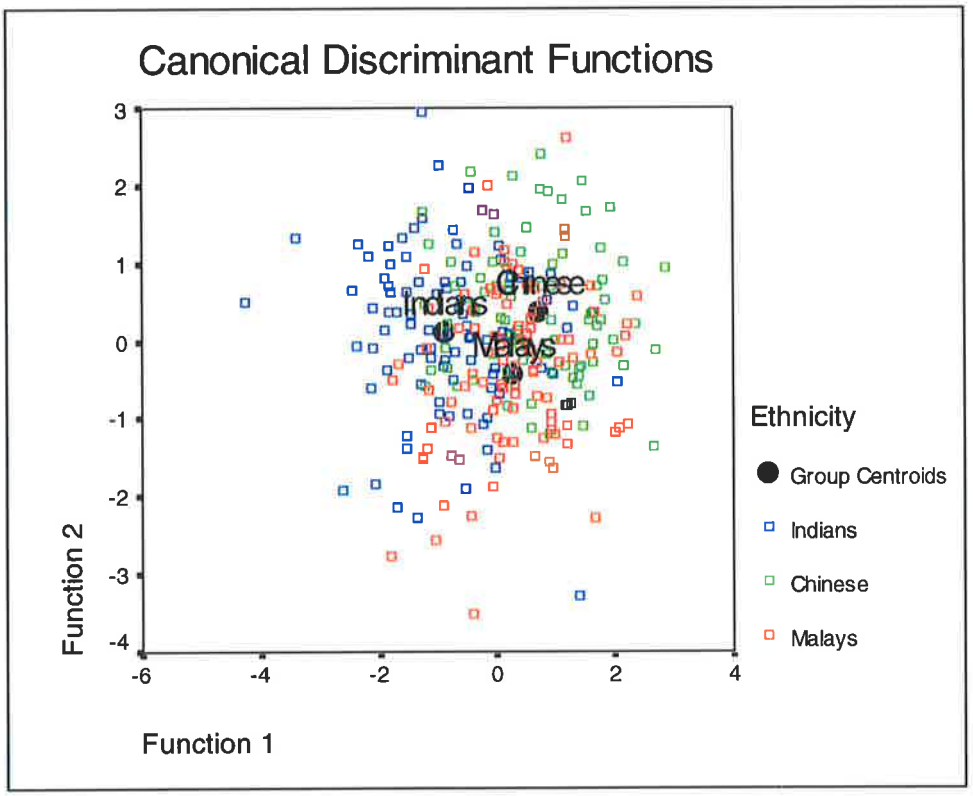
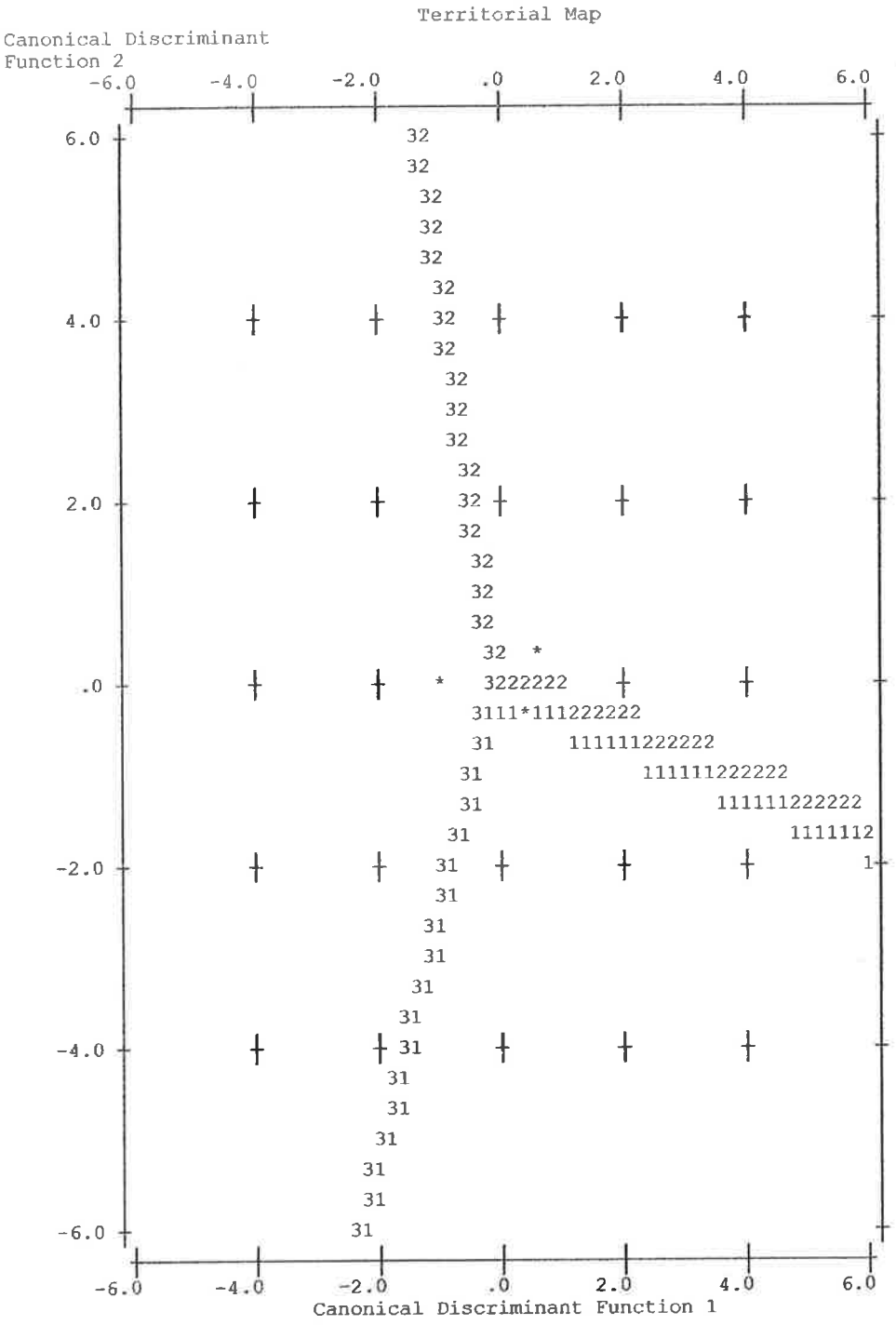


Figure 6.5 Territorial map for prediction of ethnicity using pooled-sex data (three ethnic groups)



Symbols used in territorial map

Symbol	Group	Label
1	1	Malays
2	2	Chinese
3	3	Indians
*	Indicates a group centroid	

Table 6.8 Hit ratio for prediction of ethnicity using pooled-sex data (three ethnic groups)

				Predicted Group Membership			Total
			Ethnicity	Malays	Chinese	Indians	
Cases Selected	Original	Count	Malays	80	45	33	158
			Chinese	29	91	24	144
			Indians	25	18	108	151
		%	Malays	50.6	28.5	20.9	100.0
			Chinese	20.1	63.2	16.7	100.0
			Indians	16.6	11.9	71.5	100.0
	Cross-validated	Count	Malays	76	49	33	158
			Chinese	32	88	24	144
			Indians	28	20	103	151
		%	Malays	48.1	31.0	20.9	100.0
			Chinese	22.2	61.1	16.7	100.0
			Indians	18.5	13.2	68.2	100.0
Cases Not Selected	Original	Count	Malays	15	11	6	32
			Chinese	10	17	6	33
			Indians	8	7	19	34
		%	Malays	46.9	34.4	18.8	100.0
			Chinese	30.3	51.5	18.2	100.0
			Indians	23.5	20.6	55.9	100.0

61.6% of selected original grouped cases correctly classified.
51.5% of unselected original grouped cases correctly classified.
58.9% of selected cross-validated grouped cases correctly classified.

Figure 6.6 Canonical discriminant functions for prediction of ethnicity using pooled-sex data (three ethnic groups)

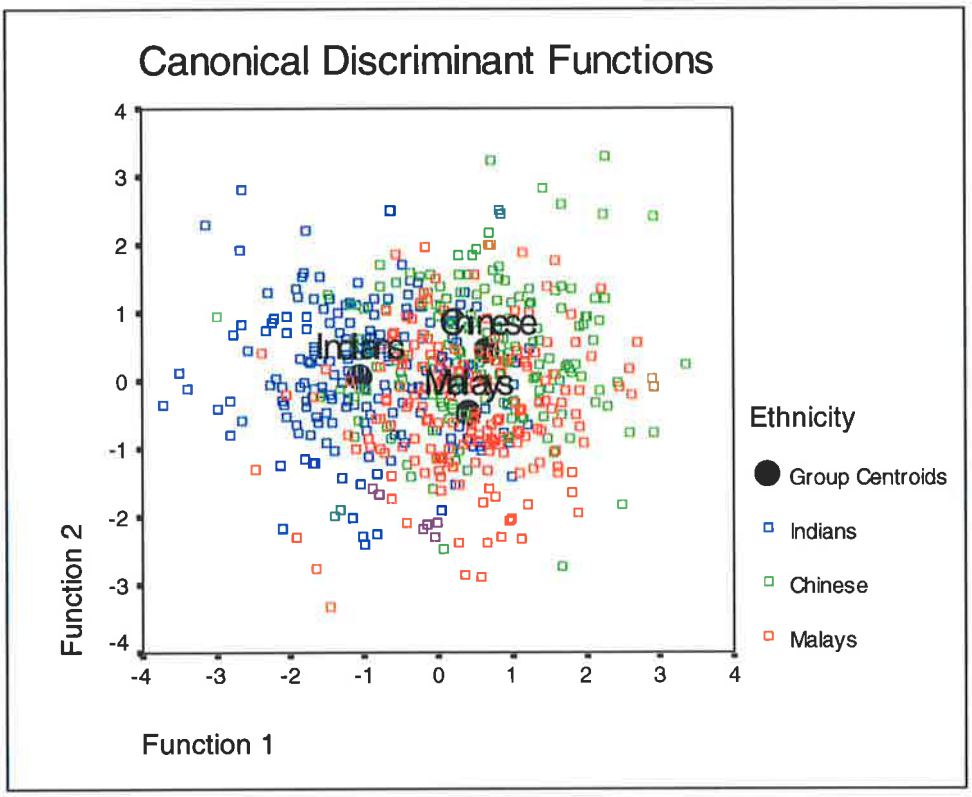


Table 6.9 Descriptive statistics for tooth size in Mongoloids and Indians

Tooth	Ethnicity	N	Mean		SD	Tooth	Ethnicity	N	Mean		SD
Mesiodistal						Mesiodistal					
UI1	Mongoloids	146	8.70		0.50	LI1	Mongoloids	146	5.52		0.32
	Indians	146	8.68		0.41		Indians	146	5.47		0.31
UI2	Mongoloids	146	7.16	***	0.57	LI2	Mongoloids	146	6.10	**	0.36
	Indians	146	6.96		0.50		Indians	146	5.99		0.36
UC	Mongoloids	146	8.15	***	0.51	LC	Mongoloids	146	7.04	***	0.47
	Indians	146	7.80		0.42		Indians	146	6.81		0.39
UP1	Mongoloids	146	7.56	***	0.44	LP1	Mongoloids	146	7.42	***	0.42
	Indians	146	7.22		0.35		Indians	146	7.25		0.37
UP2	Mongoloids	146	7.11	***	0.46	LP2	Mongoloids	146	7.40		0.43
	Indians	146	6.86		0.34		Indians	146	7.30		0.41
UM1	Mongoloids	146	10.60	*	0.49	LM1	Mongoloids	146	11.48	***	0.52
	Indians	146	10.47		0.53		Indians	146	11.19		0.55
UM2	Mongoloids	146	10.10		0.54	LM2	Mongoloids	146	10.43		0.53
	Indians	146	10.17		0.57		Indians	146	10.41		0.45
Buccolingual						Buccolingual					
UI1	Mongoloids	146	7.27		0.47	LI1	Mongoloids	146	5.89		0.35
	Indians	146	7.22		0.49		Indians	146	5.97		0.41
UI2	Mongoloids	146	6.66	*	0.48	LI2	Mongoloids	146	6.20		0.36
	Indians	146	6.53		0.47		Indians	146	6.22		0.39
UC	Mongoloids	146	8.15	***	0.53	LC	Mongoloids	146	7.27	*	0.53
	Indians	146	7.96		0.52		Indians	146	7.14		0.45
UP1	Mongoloids	146	9.71	***	0.54	LP1	Mongoloids	146	8.19		0.48
	Indians	146	9.51		0.48		Indians	146	8.14		0.44
UP2	Mongoloids	146	9.49		0.57	LP2	Mongoloids	146	8.71		0.47
	Indians	146	9.41		0.52		Indians	146	8.74		0.49
UM1	Mongoloids	146	11.44		0.59	LM1	Mongoloids	146	10.95	*	0.50
	Indians	146	11.35		0.54		Indians	146	10.84		0.48
UM2	Mongoloids	146	11.28	***	0.68	LM2	Mongoloids	146	10.63	*	0.51
	Indians	146	10.98		0.65		Indians	146	10.50		0.52

***, p<0.05; **, p<0.01; ***, p<0.001**

Table 6.10 General linear modeling multivariate analysis of variance for Mongoloids and Indians

Effect		Value	F	Hypothesis df	Error df	Sig.	Observed Power[a]
Sex	Pillai's Trace	0.388	5.91	28	261	0.0000	1.000
	Wilks' Lambda	0.612	5.91	28	261	0.0000	1.000
	Hotelling's Trace	0.634	5.91	28	261	0.0000	1.000
	Roy's Largest Root	0.634	5.91	28	261	0.0000	1.000
Ethnicity	Pillai's Trace	0.418	6.69	28	261	0.0000	1.000
	Wilks' Lambda	0.582	6.69	28	261	0.0000	1.000
	Hotelling's Trace	0.718	6.69	28	261	0.0000	1.000
	Roy's Largest Root	0.718	6.69	28	261	0.0000	1.000
Sex*Ethnicity	Pillai's Trace	0.073	0.74	28	261	0.8331	0.672
	Wilks' Lambda	0.927	0.74	28	261	0.8331	0.672
	Hotelling's Trace	0.079	0.74	28	261	0.8331	0.672
	Roy's Largest Root	0.079	0.74	28	261	0.8331	0.672

a, Computed using alpha = .05

Table 6.11 Stepwise procedures for sex prediction in Mongoloids and Indians

Step		Min. D Squared Statistic	Between Groups	Exact F Statistic	df1	df2	Sig.
1	SMEAN(RL_L3_MD)	0.797	Females and Males	58.178	1	290	0.000
2	SMEAN(RL_L7_MD)	1.005	Females and Males	36.541	2	289	0.000
3	SMEAN(RL_L4_MD)	1.311	Females and Males	31.686	3	288	0.000
4	SMEAN(RL_U4_BL)	1.528	Females and Males	27.602	4	287	0.000
5	SMEAN(RL_U2_MD)	1.628	Females and Males	23.448	5	286	0.000
6	SMEAN(RL_L3_BL)	1.712	Females and Males	20.471	6	285	0.000
7	SMEAN(RL_U1_BL)	1.841	Females and Males	18.800	7	284	0.000

At each step, the variable that maximizes the Mahalanobis distance between the two closest groups is entered.
Maximum number of steps is 56.
Minimum partial F to enter is 3.84.
Maximum partial F to remove is 2.71.
F level, tolerance, or VIN insufficient for further computation.

Table 6.12 Hit ratio for sex prediction (using both Mongoloids and Indians)

				Predicted Group Membership		Total
			Sex	Females	Males	
Cases Selected	Original	Count	Females	114	32	146
			Males	37	109	146
		%	Females	78.1	21.9	100.0
			Males	25.3	74.7	100.0
	Cross-validated	Count	Females	114	32	146
			Males	39	107	146
		%	Females	78.1	21.9	100.0
			Males	26.7	73.3	100.0
Cases Not Selected	Original	Count	Females	27	7	34
			Males	9	25	34
		%	Females	79.4	20.6	100.0
			Males	26.5	73.5	100.0

b 76.4% of selected original grouped cases correctly classified.
c 76.5% of unselected original grouped cases correctly classified.
d 75.7% of selected cross-validated grouped cases correctly classified.

Table 6.13 Stepwise procedures for sex prediction in Mongoloids

Step	Entered	Min. D Squared					
		Statistic	Between Groups	Exact F Statistic	df1	df2	Sig.
1	SMEAN(RL_U6_BL)	0.6912	Females and Males	25.23	1	144	0.000
2	SMEAN(RL_L7_MD)	0.9595	Females and Males	17.39	2	143	0.000
3	SMEAN(RL_L5_MD)	1.1491	Femalesand Males	13.79	3	142	0.000
4	SMEAN(RL_L3_MD)	1.4540	Females and Males	12.99	4	141	0.000
5	SMEAN(RL_L2_MD)	1.6463	Females and Males	11.68	5	140	0.000

At each step, the variable that maximizes the Mahalanobis distance between the two closest groups is entered.

a Maximum number of steps is 56.

b Minimum partial F to enter is 3.84.

c Maximum partial F to remove is 2.71.

d F level, tolerance, or VIN insufficient for further computation.

Table 6.14 Hit ratio matrix for sex prediction using Mongoloid data

				Predicted Group Membership		Total
			Sex	Females	Males	
Cases Selected	Original	Count	Females	54	19	73
			Males	24	49	73
		%	Females	74.0	26.0	100.0
			Males	32.9	67.1	100.0
	Cross-validated	Count	Females	54	19	73
			Males	25	48	73
		%	Females	74.0	26.0	100.0
			Males	34.2	65.8	100.0
Cases Not Selected	Original	Count	Females	14	3	17
			Males	3	14	17
		%	Females	82.4	17.6	100.0
			Males	17.6	82.4	100.0

70.5% of selected original grouped cases correctly classified.
82.4% of unselected original grouped cases correctly classified.
69.9% of selected cross-validated grouped cases correctly classified.

Table 6.15 Stepwise procedures for prediction of ethnicity using male data (Mongoloids vs Indians)

Step	Entered	Min. D Squared					
		Statistic	Between Groups	Exact F			
				Statistic	df1	df2	Sig.
1	SMEAN(RL_U4_MD)	0.8128	Mongoloids and Indians	29.67	1	144	0.000
2	SMEAN(RL_L5_MD)	1.2234	Mongoloids and Indians	22.17	2	143	0.000
3	SMEAN(RL_U3_MD)	1.4872	Mongoloids and Indians	17.84	3	142	0.000
4	SMEAN(RL_U1_MD)	1.7751	Mongoloids and Indians	15.86	4	141	0.000
5	SMEAN(RL_L6_MD)	2.0250	Mongoloids and Indians	14.37	5	140	0.000
6	SMEAN(RL_U7_MD)	2.3884	Mongoloids and Indians	14.02	6	139	0.000

At each step, the variable that maximizes the Mahalanobis distance between the two closest groups is entered.
Maximum number of steps is 56.
Minimum partial F to enter is 3.84.
Maximum partial F to remove is 2.71.
F level, tolerance, or VIN insufficient for further computation.

Table 6.16 Hit ratio matrix for prediction of ethnicity using male data (Mongoloids vs Indians)

				Predicted Group Membership		Total
			Ethnicity	Mongoloids	Indians	
Cases Selected	Original	Count	Mongoloids	61	12	73
			Indians	17	56	73
		%	Mongoloids	83.6	16.4	100.0
			Indians	23.3	76.7	100.0
	Cross-validated	Count	Mongoloids	56	17	73
			Indians	19	54	73
		%	Mongoloids	76.7	23.3	100.0
			Indians	26.0	74.0	100.0
Cases Not Selected	Original	Count	Mongoloids	14	3	17
			Indians	5	12	17
		%	Mongoloids	82.4	17.6	100.0
			Indians	29.4	70.6	100.0

80.1% of selected original grouped cases correctly classified.
76.5% of unselected original grouped cases correctly classified.
75.3% of selected cross-validated grouped cases correctly classified.

Table 6.17 Stepwise procedures for prediction of ethnicity using female data (Mongoloids vs Indians)

Step	Entered	Min. D Squared					
		Statistic	Between Groups	Exact F			
				Statistic	df1	df2	Sig.
1	SMEAN(RL_U4_MD)	0.6074	Mongoloids and Indians	22.17	1	144	0.000
2	SMEAN(RL_U7_MD)	0.9693	Mongoloids and Indians	17.57	2	143	0.000
3	SMEAN(RL_U7_BL)	1.3439	Mongoloids and Indians	16.12	3	142	0.000
4	SMEAN(RL_L5_BL)	1.6226	Mongoloids and Indians	14.50	4	141	0.000
5	SMEAN(RL_U5_MD)	2.0416	Mongoloids and Indians	14.49	5	140	0.000
6	SMEAN(RL_U3_MD)	2.2364	Mongoloids and Indians	13.13	6	139	0.000

At each step, the variable that maximizes the Mahalanobis distance between the two closest groups is entered.
Maximum number of steps is 56.
Minimum partial F to enter is 3.84.
Maximum partial F to remove is 2.71.
F level, tolerance, or VIN insufficient for further computation.

Table 6.18 Hit ratio matrix for prediction of ethnicity using female data (Mongoloids vs Indians)

				Predicted Group Membership		Total
			Ethnicity	Mongoloids	Indians	
Cases Selected	Original	Count	Mongoloids	59	14	73
			Indians	17	56	73
		%	Mongoloids	80.8	19.2	100.0
			Indians	23.3	76.7	100.0
	Cross-validated	Count	Mongoloids	56	17	73
			Indians	17	56	73
		%	Mongoloids	76.7	23.3	100.0
			Indians	23.3	76.7	100.0
Cases Not Selected	Original	Count	Mongoloids	13	4	17
			Indians	8	9	17
		%	Mongoloids	76.5	23.5	100.0
			Indians	47.1	52.9	100.0

78.8% of selected original grouped cases correctly classified.
64.7% of unselected original grouped cases correctly classified.
76.7% of selected cross-validated grouped cases correctly classified.

Table 6.19 Stepwise procedures for prediction of ethnicity using pooled-sex data (Mongoloids vs Indians)

		Min. D Squared					
Step	Entered	Statistic	Between Groups	Exact F Statistic	df1	df2	Sig.
1	SMEAN(RL_U4_MD)	0.6880	Mongoloids and Indians	50.22	1	290	0.000
2	SMEAN(RL_U7_MD)	1.0030	Mongoloids and Indians	36.48	2	289	0.000
3	SMEAN(RL_U3_MD)	1.2575	Mongoloids and Indians	30.39	3	288	0.000
4	SMEAN(RL_U1_MD)	1.5585	Mongoloids and Indians	28.15	4	287	0.000
5	SMEAN(RL_L6_MD)	1.8029	Mongoloids and Indians	25.96	5	286	0.000
6	SMEAN(RL_L5_BL)	2.0164	Mongoloids and Indians	24.11	6	285	0.000
7	SMEAN(RL_U7_BL)	2.1484	Mongoloids and Indians	21.94	7	284	0.000
8	SMEAN(RL_L1_BL)	2.2492	Mongoloids and Indians	20.03	8	283	0.000

At each step, the variable that maximizes the Mahalanobis distance between the two closest groups is entered.

a Maximum number of steps is 56.

b Minimum partial F to enter is 3.84.

c Maximum partial F to remove is 2.71.

d F level, tolerance, or VIN insufficient for further computation.

Table 6.20 Hit ratio matrix for prediction of ethnicity using pooled-sex data (Mongoloids vs Indians)

				Predicted Group Membership		Total
			Ethnicity	Mongoloids	Indians	
Cases Selected	Original	Count	Mongoloids	113	33	146
			Indians	35	111	146
		%	Mongoloids	77.4	22.6	100.0
			Indians	24.0	76.0	100.0
	Cross-validated	Count	Mongoloids	113	33	146
			Indians	37	109	146
		%	Mongoloids	77.4	22.6	100.0
			Indians	25.3	74.7	100.0
Cases Not Selected	Original	Count	Mongoloids	24	10	34
			Indians	12	22	34
		%	Mongoloids	70.6	29.4	100.0
			Indians	35.3	64.7	100.0

b 76.7% of selected original grouped cases correctly classified.

c 67.6% of unselected original grouped cases correctly classified.

d 76.0% of selected cross-validated grouped cases correctly classified.

Figure 6.7 Individual discriminant score for Mongoloids and Indians (pooled-sex data)

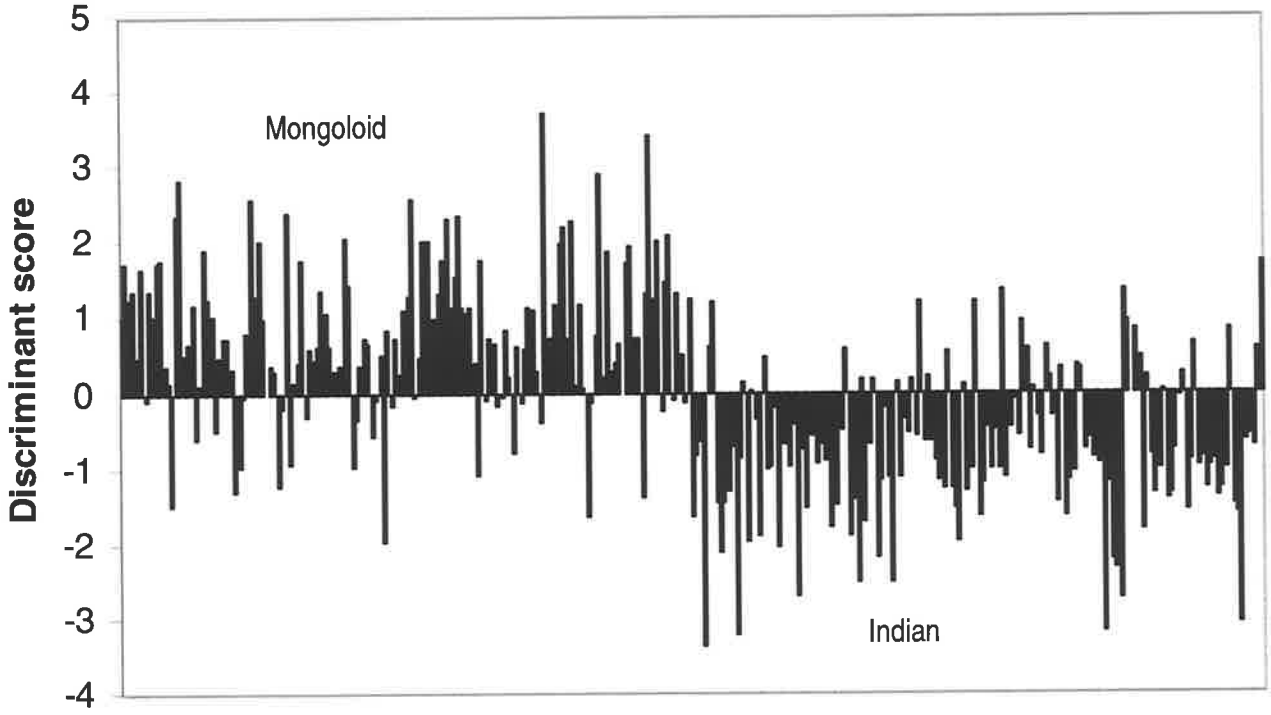


Table 6.21 List of hit ratio using different inputs for prediction of ethnicity using pooled-sex data (Mongoloids and Indians)

Input	Variables	Coefficients	Original	Test	L-O-O	Proportion chance criterion			Press's Q		
						Original	Test	L-O-O	Original	Test	L-O-O
All MD maxilla	SMEAN(RL_U1_MD)	-1.21776	71.9%	72.1%	71.2%	S	S	S	S	S	S
	SMEAN(RL_U3_MD)	1.42036									
	SMEAN(RL_U4_MD)	2.15086									
	SMEAN(RL_U7_MD)	-1.01573									
	(Constant)	-6.35217									
All BL maxilla	SMEAN(RL_U7_BL)	1.50520	54.1%	44.1%	54.1%	S	NS	S	S	NS	S
	(Constant)	-16.7491									
All MD mandible	SMEAN(RL_L3_MD)	1.38537	62.3%	54.4%	62.0%	S	S	S	S	NS	S
	SMEAN(RL_L6_MD)	1.37339									
	SMEAN(RL_L7_MD)	-1.04967									
	(Constant)	-14.2239									
All BL mandible	SMEAN(RL_L1_BL)	-2.25619	60.3%	55.9%	59.6%	S	S	S	S	NS	S
	SMEAN(RL_L3_BL)	1.65075									
	SMEAN(RL_L5_BL)	-1.15708									
	SMEAN(RL_L6_BL)	1.53802									
	(Constant)	-5.17743									

6.4 Discussion

The data used for analyses in this Chapter met the statistical assumptions for MANOVA and DFA. The results of analyses are discussed under two headings: comparison of three ethnic groups and Mongoloids versus Indians.

6.4.1 Comparison of three ethnic groups

The discriminant functions generally account for a relatively small amount of the total variation, up to around 40%, and enabled discrimination between groups with around 50% to 65% hit ratios. The functions in the male groups classified ethnicity better than in the female groups and were similar to those based on the sexes pooled. This supports the approach of Matsumura and Hudson (2005) in using only male subjects in their study of South East Asians.

The distribution of cases around their respective centroids for each ethnic group indicated considerable overlapping of tooth size discriminant scores. Such overlapping suggests the existence of some genetic admixture sometime in earlier generations or may reflect differential responses to environmental effects on tooth size development.

Function 1 discriminated unequivocally Indians from Malays and Chinese. Function 2, however, did not clearly show group separations. These patterns of relationships could be observed in separate-sex and pooled-sex data. The result of the discriminant function analysis that generated Function 1 was consistent with the outcomes of the Penrose shape distance analysis described in Chapter 4. The dendrogram in Chapter 4 suggested that Malays and Chinese were more closely related than Indians. This is consistent with the widely accepted view of anthropologists. For example, Montagu (1960), Coon (1962), Bellwood (1978) and Turner (1990) have described the Malays as southern Mongoloids which is consistent with my findings. A close relationship is also supported by the history of migrations of these people. The majority of the Chinese living in Malaysia originated from southern China (Zainuddin, 2003). Turner (1990) has indicated that the dentition of southern Chinese is quite similar to southern Mongoloids. Furthermore, southern China is quite close geographically to South East Asia and shares a similar climate. My results are also in consistent with the grouping described by Tratman (1950), who combined Malays and Chinese as Mongoloid.

Hanihara and Ishida (2005) and Kieser *et al.* (1985) have suggested that metric analysis is useful in population characterization. However, they have claimed that comparisons based on metric comparisons are only suitable for comparing between groups at a regional level. They have also emphasised the tendency for intra-regional variation to be larger when

compared with inter-regional variation. Thus, the decision to combine Malays and Chinese to represent a Mongoloid group for further analyses seems justified.

6.4.2 Mongoloids versus Indians

Similar steps were conducted to assess factor interaction effects for the second approach comparing Mongoloid and Indian samples. Since the power of study for interaction effects was less than 80%, the alpha level was increased from 5% to 10% for interpretation. At this level, the interaction effect of sex and ethnicity was still not significant. Haeussler *et al.* (1989), who compared two African groups, suggested that sexual dimorphism did not affect ethnic group classification.

In univariate analyses, 16 variables were found to be significantly larger in Mongoloids. None of the tooth size variables in Indians were larger than those in the Mongoloids. From observation of the variables which were not significant and the lack of power of the study (<80%), the mean differences were approximately less than 0.13mm. No meaningful biological interpretation can be made with differences of this magnitude.

Using both Mongoloid and Indian data, the sex prediction hit ratio was comparable with results for sex prediction using the data from three ethnic groups described in Chapter 5. Seven predictors were selected as the most discriminating variables for sex, including representatives of incisor, canine, premolar and molar teeth. The mesiodistal dimension of the lower canine was the most dimorphic variable. The combinations of predictor variables obtained in this Chapter differed from those obtained in Chapter 5, with only four predictors being similar. However, comparable values for hit ratios in the test sample in both studies, 81.8% in chapter 5 and 76.5% in this Chapter, lend some assurance to the practicality of the forensic applications. Discriminant functions generated in this Chapter used fewer predictors (seven predictors) than the prediction model using pooled ethnic group data (Appendix 5.27) which identified 12 predictors. Even though the hit ratio in the analysis in this Chapter was slightly lower, the function consisting of seven predictors would be less likely to be affected by missing values. Both discriminant functions are suitable for predicting sex in cases of unknown ancestry/ethnicity for Malaysians. The main advantage in using the function calculated in Chapter 5 would be its higher hit ratio. However, the discriminant function derived in this Chapter could be used as an alternative in situations where there are missing teeth that preclude inclusion of all 12 predictors.

Comparisons of hit ratios for sex prediction in the test sample and the combination of predictor variables in the Mongoloid group with those for Malays and Chinese described in

Chapter 5 reveal comparable results for hit ratio values but differences in the combination of predictor variables. Only one predictor variable in discriminant function generated for Mongoloids was similar with those for Malays and Chinese; that is, the mesiodistal diameter of the lower canine in Malays and the mesiodistal diameter of the lower second molar in Chinese. Since both test sample showed similar outcomes, functions from either the Mongoloid group, or Malays and Chinese as described in Chapter 5 could be used to predict sex. The advantage in using a discriminant function derived from Mongoloids would be that it is less ethnicity specific and its hit ratio is reasonably high.

Prediction models were generated with stepwise discriminant function analysis using 28 variables to discriminate between Mongoloids and Indians for separate-sex and pooled-sex data. By knowing a specimen's sex, the prediction of ethnicity between Mongoloids and Indians would be improved. The hit ratio for ethnicity prediction was higher using male data than sex-pooled (unknown sex data). The function derived from female data generated a hit ratio that was not statistically significant for the test sample. This means that the function based on data from females would not be useful practically. Only two functions were suitable for ethnicity prediction, those derived for known male or unknown sex specimens. In essence, odontometry provides a useful way of discriminating Mongoloids and Indians, even though knowing that a specimen was female would not improve the prediction rate. In comparisons between the three ethnic groups, DFA hit ratios did not differ much whether the sex of the case was known or not. Slight improvement was noted in using sex pooled data which could provide an advantage. This means in cases of unknown sex, ethnicity prediction into one of the three ethnic groups; Malays, Chinese and Indians could only be made confidently 52-62% of the time.

Other input combinations into the stepwise procedures were attempted, bearing in mind forensic applications. Using mesiodistal diameters of maxillary teeth as input, improved hit ratios in the test sample and was comparable with the function derived from 28 variables. Overall, hit ratios for ethnic prediction were lower than those for sex prediction reported in Chapter 5. From several input combinations, only two functions seemed appropriate for forensic application to discriminate Mongoloids from Indians, even though the hit ratios were not as high as in the studies by Matis and Zwemer (1971), Haeussler *et al.* (1989), and Chiu and Donlon (2000). Both functions used 28 variables and included the mesiodistal diameters of all maxillary teeth.

Models comparing the three ethnic groups and those between Mongoloids versus Indians can be considered from the point of view of sensitivity and specificity. The hit ratio for distinguishing Mongoloids from Indians is less specific but more sensitive. Less specific

because classification into the Mongoloid group does not specify Malays or Chinese, but more sensitive due to a better hit ratio than for the three ethnic group classification. One of the possible ways for conducting analyses, if all variables could be recorded in forensic situation, would be to apply a two-step discrimination approach. The first step would separate Indians from Mongoloids and subsequently, discriminant functions from three ethnic groups could be used to discriminate Malays and Chinese.

The predictors selected from stepwise procedures as being most discriminative (Mongoloids versus Indians) were different to those found by Chiu and Donlon (2000). The latter authors found that premolar dimensions dominated as predictor variables when discriminating between Mongoloids and Caucasoids. In the present study, only two predictors comprising premolar dimensions were included in the first function and only the mesiodistal dimensions of upper premolars were included for the second function, suggesting that premolar size was not a 'racial marker' for Mongoloid populations.

In conclusion, odontometry would appear to be suitable for use in forensic practice to discriminate between ethnic groups. Even though around 24% of the individuals were misclassified in this study, the process of identity reconstruction would be supplemented with other evidence including sex, height and age at the time of death. In addition, the main purpose of reconstructive identity is to narrow down the search for potential ante-mortem records for comparative identification processes. Other than for forensic application, canonical discriminant variates confirmed the usefulness of Penrose shape distance analyses in assessing population relationships/affinities.

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Chapter 7 Morphological variations of teeth in Malaysian populations

7.1 Introduction

In terms of historical migrations and interrelationships of people, Malaysia has been compared to the United States of America (Nagata, 1979); that is, home to many different people from different ethnic backgrounds. This study concentrates on the three major ethnic groups in Malaysia; Malays, Chinese and Indians, and a small group of Negritos.

Two models have been proposed to describe the origin of Southeast Asians. The first model was referred to as the 'dual layer' model by Jacob (1967) or the immigration model by Matsumura and Majid (1999). It suggests that genetic mixture through interbreeding occurred between early settlers of South East Asia, who possessed Australomelanesoid features, and Mongoloid peoples from China. Turner (1987, 1990) proposed an alternative regional continuity model that suggested that modern South Asians evolved locally rather than originating through genetic admixture.

Tratman (1950) described dental variations between Mongoloids and Indians from the Malaysian Peninsula and Singapore. He combined Malays and Chinese into one regional group for his comparisons, while Indians were categorized as representing Indo-Europeans. He highlighted several anatomical differences between the groups. His report was limited to anatomical description without statistical analyses (except for a few traits) due to loss of data during World War II. The Mongoloids showed a high frequency of shovelling, dens evaginatus of the premolars, double shovel, enamel extension (90% prevalence), taurodontism in upper and lower molars, sixth cusp on the lower first molar, short roots on all teeth, relatively small crowns and roots of the canine and maxillary premolars, single or fused roots in upper premolars (1^{st} and 2^{nd}), complex occlusal surfaces in the molar series, large sized lower molar crowns, less prevalence of Carabelli trait, less splayed roots of maxillary molars and an extra distolingual root (10% prevalence).

Another report on the dentition of Malaysians by Rusmah (1992) presented statistical frequencies for Carabelli cusp. The feature was present in 52.2% of the sample. Rusmah also reported that no sexual dimorphism or bilateral asymmetry was evident in this population but there were several statistical errors in the analysis. Table 1 in the original paper gave a chi-square value of 0.56, with one degree of freedom, and noted that the associated probability was $p<0.001$. Using SPSS and the frequency count given in Rusmah's Table 1, my

calculations indicate a chi-square value of 0.392, with one degree of freedom, is associated with a p value of 0.531. At this probability level, the null hypothesis that there is no difference in the frequency of Carabelli in males and females would be retained. Similarly, for Rusmah's Table 2, the reported chi-quare value of 1.56, with four degrees of freedom, was reported as being associated with a p value of less than 0.001. My calculation using the data in Rusmah's Table 2 indicates a chi-square value 0.788, with four degrees of freedom, and a probability of 0.940. Despite these statistical errors, the general interpretation in Rusmah's paper is still valid. However, one limitation of the study was that, even though the sample size was large, the author did not specify the ethnicity of the participants.

Tooth morphology has been used successfully in anthropology because teeth are generally hard and robust, do not decompose and are reasonably fire-resistant. Dahlberg (1963, 1985) indicated that tooth morphology can also be useful in forensic applications, particularly in reconstructive identification processes. Dental traits proposed by Dahlberg (1963) as suitable for use in forensic circumstances include cusp size, number and location; simple and complex occlusal cusp-groove surface patterns; individual tooth measurements; dimensional proportions between kinds of teeth (second premolar: first molar); and number and arrangement of teeth.

Irrespective of whether dental traits are used for anthropologic or forensic applications, the main working principles are centered on the assumption of strong genetic determination and individuality of the trait or group of traits selected (Dahlberg, 1957). A group of dental traits that characterize a population was first referred to as a "dental complex" by Hanihara (1967). He proposed the term "Mongoloid dental complex" which comprised six deciduous crown morphologies that occurred with high frequencies; namely, shovel shape on the upper central and lateral incisors, deflecting wrinkle, protostylid, seventh cusp on the lower second molar, and metaconule on the upper second molar. He suggested further exploration and application of dental complexes for permanent teeth in both Mongoloid and other racial groups. In 1968, he proposed a Mongoloid dental complex for permanent teeth, which was similar to that for the deciduous dentition, except that cusp 7 was excluded (Hanihara, 1968).

Subsequently, Turner (1987, 1990) found that Mongoloid people could be subdivided into Sinodonts, represented by Northern Asians and Native Americans, and Sundadonts comprising peoples of South East Asia. He analysed 28 dental traits derived from several East Asian populations, including recent and prehistoric samples, involving both crown and root morphologies. The dental traits were as follows: winging UI1, shovelling UI1, double-shovelling UI1, interruption grooves UI2, tuberculum dentale UI2, mesial ridge UC, distal accessory ridge

UC, hypocone UM2, cusp 5 UM1, Carabelli trait UM1, parastyle UM3, enamel extension UM1, root number UP1, root number UM2, peg/reduced/congenital absence UM3, lingual cusp number LP2, groove pattern LM2, cusp number LM1, cusp number LM2, deflecting wrinkle LM1, distal trigonid crest LM1, protostylid LM1, cusp 7 LM1, Tome's root LP1, root number LC, root number LM1, root number LM2, and odontome U+LP 1 and 2. He used the Mean Measure of Divergence (MMD) to assess biological distance between East Asian people. The MMD matrix was presented as a cluster analysis for ease of interpretation. From the cladogram, he concluded that East Asians could be divided into those who lived in the Northern and South East areas of East Asia. In addition to the two major clusters, the South East Asian (Sundadont) grouping could be further divided into two minor clusters, with people from Nepal, the Philippines, East Malay Archipelago, Indomalaysia and Burma in the first minor cluster and Prehistoric Taiwanese, Thais, Early Mainland South East Asians, from Early Malay Archipelago and recent South East Asians (people from Indochina) in the second minor cluster. Turner was not able to provide a definite explanation for these Sundadont minor clusters. He tentatively suggested that the Sundadont subdivisions could be due to admixture between people from the first minor cluster with neighbouring Caucasoids from India, or influence from Arab and Indian traders, missionaries and colonists, or even from Sinodonts/northern Mongoloids. The rationale behind this explanation related to the fact that the first minor cluster represents recent populations whereas the second minor cluster comprises prehistoric populations who were more likely to be genetically isolated. His explanation was restricted, as it did not include an Asiatic Indian sample. Inclusion of an Asiatic Indian sample to compare with the Malays and Chinese would help to clarify the possibility of Caucasoid and Sinodont admixture in the first minor cluster.

From 28 traits initially used to separate East Asians into North and South divisions, Turner (1990) found eight dental traits that discriminated between the Sinodonts and Sundadonts. These traits were shovelling UI1, double shovel UI1, LM1 deflecting wrinkle, UM1 enamel extension, UM3 peg/reduced/congenital absence, 3-rooted LM1, 4-cusped LM2 and one-rooted UP1. All traits occurred more frequently in Sinodonts, except for 4-cusped LM2. Turner described the Sinodonts as having trait intensification, that is, higher frequencies of crown trait occurrence and addition (e.g. three rooted LM1), while the Sundadonts showed crown simplification or moderate frequencies of occurrence, and retention of old traits (two rooted UP1).

A number of researchers have reported findings that contradict the concept of racial dental complexes. One of the traits that has been extensively studied is Carabelli trait, which

has been widely accepted as a racial marker for Caucasoids (Mayhall *et al.*, 1982). However, both Kraus (1959) and Hershey (1979) suggested that Carabelli trait was actually more frequent in Mongoloids than in Caucasoids. Hershey reported high pit and intermediate expressions and high overall trait presence (92%) of Carabelli trait in Wainwright Eskimos, who belong to Mongoloid stock. Not only has the validity of Carabelli trait as a racial trait been challenged, researchers have also questioned the value of the deflecting wrinkle and entoconulid (C6) as features characteristic of the Mongoloid dental complex (Axelsson and Kirveskari, 1977; Axelsson and Kirveskari, 1979). They found that the frequencies of the deflecting wrinkle (34.2% on LM1) and entoconulid (17% on LM1) (C6) in Icelanders, who are considered to be Caucasoids, fell within the range of Mongoloid populations. Reiterating the cautious remark made by Dahlberg (1957), Mayhall (1999) emphasized the crucial need for knowledge of the genetic basis of every dental trait selected for population characterization.

An important consideration before characterizing populations is within-group variation, encompassing the extent of sexual dimorphism, bilateral asymmetry and inter-trait associations. In a review by Scott and Turner (1997), it was concluded that tooth morphology was suitable for population characterization due to its low sexual dimorphism and strong symmetry. Several researchers have found no significant sexual dimorphism for dental traits (Garn *et al.*, 1966b; Bang and Hasund, 1971; Bang and Hasund, 1972; Hanihara, 1977; Turner and Hanihara, 1977; Turner and Scott, 1977; Hershey, 1979; Scott, 1980; Hassanali, 1982; Mayhall *et al.*, 1982; Kieser, 1984; Thomas *et al.*, 1986; Townsend *et al.*, 1986; Haeussler *et al.*, 1989; Townsend *et al.*, 1990; Manabe *et al.*, 1992; Rusmah, 1992; Kannappan and Swaminathan, 1998) while others have noted higher frequencies for certain features in males (Rothhammer *et al.*, 1968; Escobar *et al.*, 1977; Scott, 1977b; Townsend and Brown, 1981; Iwai-Liao *et al.*, 1996; Hsu *et al.*, 1997) and occasionally in females (Harris and Bailit, 1980). Several studies have indicated that dental traits tend to be expressed symmetrically (Baume and Crawford, 1979; Harris and Bailit, 1980; Noss *et al.*, 1983b; Townsend *et al.*, 1990) while others have reported some evidence of asymmetry (Meredith and Hixon, 1954; Mayhall and Saunders, 1986; Moskona *et al.*, 1996). Inter-trait associations tend to be strong for traits within tooth classes e.g. shovelling on the central and lateral incisors (Sofaer *et al.*, 1972; Scott, 1977a) but normally weak between different traits (Garn *et al.*, 1966a; Sofaer *et al.*, 1972; Scott, 1978; Scott, 1979; Axelsson and Kirveskari, 1982; Motayam *et al.*, 1985; Macho and Cecchi, 1992).

While assessment of dental complexes may facilitate population stratification, the potential application of dental traits in identification of individuals is likely to involve comparison

of those dental traits that provide best discrimination between ethnic groups. The results from analyses of non-metric dental traits could then be used in conjunction with the results from analysis of metric variables (e.g. tooth size) to maximize discriminatory power. Studies of within-group variation have highlighted a wide range of variation in the extent of sexual dimorphism and asymmetry between different human populations. Thus, the study described in this Chapter aims to characterize variation in dental crown traits, within-groups as well as between-groups, and to assess affinities in four major Malaysian groups based on frequencies of occurrence of their dental features.

7.2 Materials and methods

The same study models were used in the research reported in this Chapter as in the metric studies described in Chapters 4, 5 and 6. In fact, the scoring of dental traits was completed prior to the recording of tooth size measurements. A total of 790 dental models (upper and lower) were used, which is greater than the number used in the metric study. Table 7.1 shows the sample distribution according to sex and age for each ethnic group. All groups comprised teenagers from around Kelantan and Perak, except for the Negritos who comprised older participants. Logistic, financial and time constraints restricted the number of Negritos who could be recruited into the study. The small number of Negritos (Jahai) provides limited statistical power (Appendix 7.1), so results for this group should be interpreted with caution.

The classification for crown traits, except those for the entoconulid, Carabelli trait and groove pattern, were simplified from the Arizona State University (ASU) classification (Turner *et al.*, 1991). In addition, the ASU reference plaques were used for all traits to provide extra guidance. The definition of Townsend *et al.* (1990) was used for entoconulid classification, as it includes observation of the entoconulid on four-cusped molars, whereas the ASU system only scores entoconulids on five-cusped molars. Carabelli trait was scored according to Dahlberg's plaque P12A and groove pattern was assessed using plaque P10 (Dahlberg, 1956).

During training and familiarization of the ASU classifications, some difficulties were encountered when using the multi-grade scoring method. After discussion with an experienced researcher (personal communication with Dr Kondo), the original ASU gradings were simplified into two or three grades of expression only (Table 7.2). Table 7.2 provides the breakpoints chosen for the dichotomous data.

167 dental casts were scored twice and the intra-observer errors for graded scales and presence/absence for all traits were reported as percentages of discordance (Nichol and Turner, 1986). These authors set 10% discordance as the benchmark for 2-grade discrepancies and presence-absence data. Inter-observer error was tested using 29 dental casts measured by Dr Shintaro Kondo, for eight dental traits on the right side only; winging of upper incisors, shovelling, carabelli trait, entoconulid, distal accessory ridge, protostylid, lingual cusp number on the lower second premolar and groove pattern on the second molar.

The extent of asymmetry in males was compared with that in females using chi-square analysis and Fisher's exact test when expected cell frequencies were less than five (Howitt and Cramer, 2003). Absent-absent pairs were excluded from analysis. These preliminary tests were

used to determine whether it would be appropriate to pool data for subsequent analyses of symmetry. An adjusted alpha level was set at 0.05/12=0.004 (Bonferroni's adjustment).

Comparisons of the frequencies of occurrence of dental traits on corresponding right and left teeth were tested using non-parametric analyses. In cases where the author's PC computer had insufficient memory to calculate Fisher's exact test, the Monte Carlo Estimate was applied. The Monte Carlo Estimate is "an [sic] unbiased estimate of the exact significance level, calculated by repeatedly sampling from a reference set of tables with the same dimensions and row and column margins as the observed table...This method is most useful when the data set is too large to compute exact significance, but the data do not meet the assumptions of the asymptotic method" (SPSS Inc., 1989-2001, version 11.0.1).

Basic descriptive statistics were presented as percentage frequencies of occurrence and degrees of expression. Sexual dimorphism was assessed using univariate non-parametric analyses. Bonferroni's adjustment was adopted for multiple univariate testing (13 independent variables) to control Type 1 error. The alpha level of 0.05 was divided by 13, yielding an adjusted alpha value of 0.004.

The process of calculating the Mean Measure of divergence (MMD) was simplified, as shown in Figure 7.1, by taking account of the issues raised by Harris and Sjovold (2004) about problems and possible mistakes in the computation of MMD statistics. Ethnic group differences in the frequencies of occurrence of 13 dental traits were analysed using chi-square analysis at an alpha level of 0.05. The tests were important for selection of traits, as only those traits associated with a significant outcome were used as input into the mean measure of divergence (MMD) computations to avoid negative values. Negative MMD coefficients were replaced with zero only if the coefficients were to be used for subsequent graphical representation.

The MMD analysis utilized dichotomous data. The frequencies of occurrence were transformed using Anscombe computations (Equation 2) to stabilize sampling variance. Harris and Sjovold (2004) defined the computation of the MMD as follows: "the difference between samples i and j for the frequencies of trait k is calculated and then this difference is squared and the correction term is subtracted. The sum of corrected squared differences was averaged according to the number of traits".

$$\text{Mean measure of divergence (MMD)} = (1/r) \sum_{k=1}^{r} \left((\theta_{ik}-\theta_{jk})^2-(1/((n_{ik}+0.5) +1/(n_{jk}+0.5)) \right) \quad \text{.....equation 1}$$

r, number of traits

k, dental traits

i, j, samples from group i ,j

n_{ik}, scorable samples in i group for trait k

n_{jk}, scorable samples in j group for trait k

Anscombe's transformation, $\theta = \sin^{-1}(1-2((m+3/8)/(n+3/4)))$ ...equation 2

m, frequency of trait presence

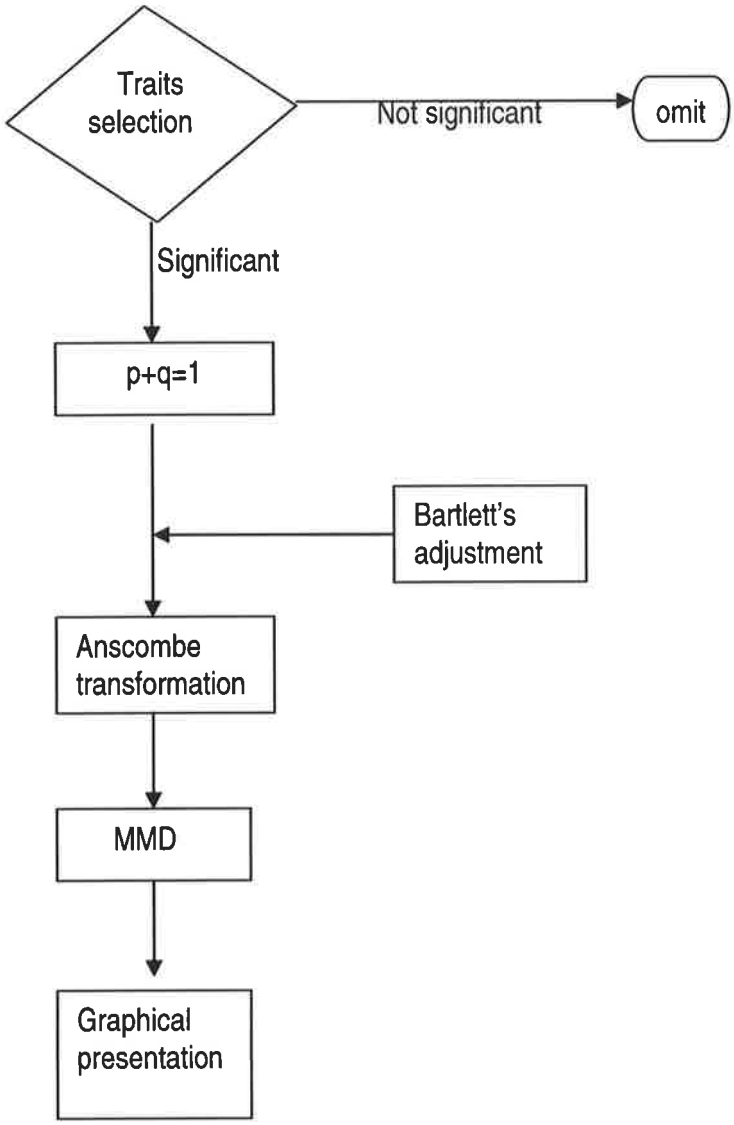
n, scorable specimens

$$\text{Standard deviation of MMD} = \left((2/r^2) \sum_{k=1}^{r} (1/n_{ik} +1/n_{jk})^2 \right)^{1/2} \quad \text{...equation 3}$$

The coefficient of MMD is considered to be significant at alpha 5% when MMD is twice its standard deviation (Equation 3). Harris and Sjovold (2004) suggested using Bartlett's adjustment when the trait frequency is extreme in a particular sample but this was not considered to be necessary in the present study.

For the ease of interpretation, MMD coefficients were used as input into a hierarchical cluster analysis to generate a classification tree dendrogram. Clustering methods used Ward's linkage and measurement between pairs of groups was based on squared Euclidean distance. The output rescaled distance to numbers between 0 and 25, thereby preserving the ratio of the distance between steps rather than the actual distances.

Figure 7.1 Flowchart showing approach to calculate the mean measure of divergence (modified from Harris and Sjovold, 2004)



p, proportion of trait presence

q, proportion of trait absence

Table 7.1 Distribution of participants according to sex and age within four ethnic groups

Ethnic group	Sex	N	Mean (years)	SD
Malays	Females	167	15.6	1.2
	Males	126	15.1	1.3
	Total	293	15.4	1.3
Chinese	Females	88	14.5	1.3
	Males	90	14.7	1.5
	Total	178	14.6	1.4
Indians	Females	131	15.8	1.4
	Males	121	15.6	1.3
	Total	252	15.7	1.3
Negritos (Jahai)	Females	33	28.3	8.2
	Males	34	30.5	13.1
	Total	67	29.4	10.9
Total	Females	419	16.4	4.4
	Males	371	16.6	6.1
	Total	790	16.5	5.2

N, sample size; SD, standard deviation

Table 7.2 Dental crown trait classification used in this study

Traits	Tooth	Classification	ASU grade	Score	Breakpoint for dichotomous data
Winging	11,21	Bilateral winging	1	1	1-present
		Unilateral winging	2	2	23-absent
		Counter wing and straight	3,4	3	
Shovel	11,21	Absent	0	0	01-absent
		Trace	12	1	23-present
		Semi	34	2	
		Shovel	56	3	
Metaconule	16,26	Absent	0	0	0-absent
		Weak cuspule	12	1	123-present
		Small cuspule	3	2	
		Small/moderate cusp	45	3	
Carabelli trait*	16,26	Absent	a	0	0-absent
		Pit & furrow	bc	1	123-present
		Tubercle	defg	2	
		Cusp	h	3	
Hypocone	17,27	Absent/ridge	0 1	0	01-absent
		Cuspule	2	1	23-present
		Reduced cusp	34	2	
		Large	56	3	
Distal accessory ridge	33,43	Absent	0	0	0-absent
		Weak	12	1	12-present
		Strong	345	2	
Lingual cusp number	35,45	One		1	1-one cusp
		Two		2	234-not one
		Three		3	cusp
		Four		4	
Protostylid	36,46	Absent	0	0	0-absent
		Weak	123	1	12-present
		Strong	4567	2	
Metaconulid	36,46	Absent	0 1.5	0	0-absent
		Small	123	1	12-present
		Large	4	2	
Entoconulid	36,46	Absent	0	0	0-absent
		Weak	12	1	12-present
		Strong	34	2	
Deflecting wrinkle	36,46	Absent	0 1	0	01-absent
		Weak	2	1	2-present
		Strong	3	2	
Cusp number	37,47	Four		4	4-four cusp
		Five		5	56-not four cusp
		Six		6	
Groove pattern^	37,47	Y	Y	1	1-Y pattern
		+	+	2	23-+, X pattern
		X	X	3	

^ observation using Dahlberg plaque P10 * observation using Dahlberg plaque P12A

7.3 Results

Intra-observer error for absence-presence was lower than for full-grade scoring. Dichotomous traits which were difficult to score reliably were shovelling, metaconule and distal accessory ridge in Malays; metaconule, distal accessory ridge, and lingual cusp number of lower second premolars in Chinese; and metaconule, distal accessory ridge, entoconulid, groove pattern and cusp number in Indians. Some dental traits were associated with errors around 20% for full-grade scoring e.g. deflecting wrinkle, distal accessory ridge, Carabelli trait, metaconule in Malays (Table 7.3), distal accessory ridge, hypocone reduction in Chinese (Table 7.4) and metaconule, deflecting wrinkle and groove pattern in Indians (Table 7.5). The differences recorded were, however, only one grade apart. Table 7.6 shows a generally low error rate in Jahai for both full-grade scoring and absent/present categorization.

Inter-observer error was higher than intra-observer error. The results indicated that inter-observer discrepancies of one grade or more were as follows: shovelling - 27.6% (one case of 2-grade discrepancy); Carabelli trait - 27.6% (one case of 2-grade discrepancy); distal accessory ridge - 17.2% (four cases of 2-grade discrepancy); lingual cusp number premolar - 20.7% (one case of 2-grade discrepancy), winging - 20.6%; entoconulid - 6.9%, protostylid - 17.2%, and groove pattern - 3.4%.

Appendices 7.2 to 7.5 show patterns of symmetry/asymmetry were similar in both sexes, except for hypocone reduction in Chinese and Jahai, and the metaconulid in Indians. Table 7.7 indicates that all dental traits in Malays were expressed symmetrically and the associated correlation coefficients between antimeres were also significant. Two dental traits only, deflecting wrinkle and groove pattern, exhibited less than 80% symmetry. Asymmetry results that were most affected when absence-absence pairs were excluded from the analysis were metaconulid, deflecting wrinkle and distal accessory ridge. Groove pattern was only moderately correlated between sides. Table 7.8 shows values of correlation coefficients between sides and symmetrical expression of dental traits in Chinese. The correlation coefficients were moderate for groove pattern, deflecting wrinkle and distal accessory ridge. The percentage concordance between sides was high for most traits, except for deflecting wrinkle, groove pattern, metaconule. When absent-absent pairs were excluded, concordances for distal accessory ridge, deflecting wrinkle and metaconulid symmetry dropped considerably. Table 7.9 shows values of correlations between sides were high in Indians, except for groove pattern which was associated with a moderate value. When absent-absent pairs were excluded, the percentage concordance between sides for expression of the metaconulid was

reduced considerably. Table 7.10 gives correlation coefficients and statistical associations between sides for the Jahai. The least symmetrical expression was shown by groove pattern, followed by the metaconule. When absent-absent pairs were excluded from analysis, concordances for the entoconulid and metaconule were reduced most. All correlation and concordance analyses yielded significant values at 5%, except for groove pattern. Moderate correlations were obtained for lingual cusp number of lower second premolars, entoconulid, groove pattern and metaconule.

Overviews of frequencies of occurrence in four ethnic groups are given in Table 7.11. Appendices 7.6 to 7.18 compare frequencies of occurrence of dental traits in the four ethnic groups. Winging of upper central incisors, shovelling, metaconule, deflecting wrinkle, groove pattern, metaconulid, protostylid, hypocone, lingual cusp number of premolar, and entoconulid showed no evidence of significant sexual dimorphism in any of the four ethnic groups. Sexual dimorphism was found to be significant at alpha 5% (Bonferroni's adjustment) for several traits, with varying degrees across the different ethnic groups. Carabelli trait was found to occur more frequently in males than females in the Chinese sample, while pits and furrows were more frequent in female Chinese. The four-cusped lower second molar was more frequent in female Chinese, whereas the distal accessory ridge was significantly more frequent in males in both Chinese and Jahai.

Table 7.12 shows significant differences in the frequencies of occurrence of 11 dental traits between the four ethnic groups. Ethnic group differences were not significant for two dental traits; entoconulid and metaconulid. Figure 7.2 compares the overall profiles of frequencies between the four ethnic groups. Malays showed intermediate frequencies of occurrences for all dental traits while the Chinese showed extreme high and low frequencies. Shovelling, winging, protostylid, deflecting wrinkle, distal accessory ridge, and one-lingual cusped premolar frequencies were high in the Chinese, whereas Carabelli trait, metaconule and four-cusped molars were the least frequently observed traits. The Indian group was characterized by a high frequency of Carabelli trait, metaconule, reduced hypocone, four-cusped lower second molars and Y- groove patterns, and a low frequency of winging, shovelling, distal accessory ridge, protostylid and entoconulid. The Jahai exhibited low frequencies of occurrences of shovelling, hypocone reduction, one-cusped premolars, deflecting wrinkle, and Y-groove patterns. Only winging frequency was found to be high in the Jahai cohort. Differences of 10% or less in frequencies of occurrence were not associated with statistical significance, as shown by the entoconulid and metaconulid.

Nine dental traits discriminated Indians from Malays and Chinese: five showed high frequencies in Malays and Chinese; namely, winging, shovelling, distal accessory ridge, protostylid, deflecting wrinkle, whereas four were associated with high frequencies in Indians, ie metaconule, hypocone reduction, four-cusped lower second molars, and Y-groove pattern. Another four dental traits were not discriminative; Carabelli trait, one-cusped premolars, entoconulid and metaconulid.

When comparing Malays and Chinese, winging, shovelling, one-cusped premolars, protostylid and deflecting wrinkle were present more frequently in Chinese, while Carabelli trait and four-cusped molars were more frequent in Malays. The other dental traits did not discriminate between Malays and Chinese.

Table 7.13 shows the MMD matrix including tests of significance and coefficients. All MMD coefficients were statistically significant at $p<0.05$. MMD coefficients derived from an average of 11 dental traits (the frequencies of entoconulid and metaconulid were not statistically significant in four ethnic groups, therefore they were excluded from the MMD analysis) were further subjected to hierarchical cluster analysis to produce a dendrogram. Figure 7.3 shows the affinities between the four ethnic groups. Indians were separated at a rescaled number of 25 from the other three groups; Malays, Jahai and Chinese. At a rescaled number of approximately 14, Chinese were separated from Malays and Jahai. Figure 7.4 shows a similar pattern of affinities between the three major groups (without the Jahai included in the analysis).

Table 7.3 Intra-observer error (% discordance) for scoring dental traits in Malays

Tooth	Trait	Full scoring*	Present/Absent
11 & 21	Winging	9.4 (53)	3.8 (53)
21	Shovelling	19.6 (51)	17.6 (51)
11		16.3 (49)	16.3 (49)
26	Carabelli trait	17.6 (51)	3.9 (51)
16		21.1 (52)	3.8 (52)
26	Metaconule (C5)	18.2 (44)	18.2 (44)
16		21.4 (42)	16.7 (42)
27	Hypocone reduction	6.3 (48)	0.0 (48)
17		11.4 (44)	4.6 (44)
43	Distal accessory ridge	17.3 (52)	7.7 (52)
33		23.1 (52)	13.5 (52)
45	Lingual cusp number	11.8 (51)	5.9 (51)
35		12.0 (50)	8.0 (50)
46	Protostylid	19.2 (52)	7.7 (52)
36		20.0 (45)	8.9 (45)
46	Deflecting wrinkle	21.8 (32)	6.3 (32)
36		13.9 (36)	0.0 (36)
46	Metaconulid	2.0 (51)	0.0 (51)
36		2.1 (48)	0.0 (48)
46	Entoconulid	7.8 (51)	3.9 (51)
36		8.9 (45)	2.2 (45)
47	Cusp number	4.1 (49)	2.0 (49)
37		4.3 (46)	4.3 (46)
47	Groove pattern	10.9 (46)	2.6 (46)
37		17.9 (39)	2.6 (39)

* A discordance of one category or more between 1st and 2nd determinations; Sample size shown in parentheses

Table 7.4 Intra-observer error (% discordance) for scoring dental traits in Chinese

Tooth	Trait	Full scoring*	Present/Absent
11 & 21	Winging	12.5 (40)	5.0 (40)
21	Shovelling	10.5 (38)	10.5 (38)
11		7.9 (38)	7.9 (38)
26	Carabelli trait	7.7 (39)	2.6 (39)
16		10.5 (38)	2.6 (38)
26	Metaconule (C5)	15.4 (39)	10.3 (39)
16		15.8 (38)	13.2 (38)
27	Hypocone reduction	20.0 (35)	0.0 (35)
17		21.8 (32)	6.3 (32)
43	Distal accessory ridge	22.2 (36)	11.1 (36)
33		18.4 (38)	10.5 (38)
45	Lingual cusp number	16.2 (37)	10.8 (37)
35		18.9 (37)	13.5 (37)
46	Protostylid	18.8 (32)	9.4 (32)
36		16.7 (36)	8.3 (36)
46	Deflecting wrinkle	8.0 (25)	8.0 (25)
36		11.1 (27)	7.4 (27)
46	Metaconulid	0.0 (38)	0.0 (38)
36		0.0 (39)	0.0 (39)
46	Entoconulid	13.2 (38)	5.3 (38)
36		11.1 (36)	2.8 (36)
47	Cusp number	0.0 (30)	0.0 (30)
37		0.0 (31)	0.0 (31)
47	Groove pattern	0.0 (27)	0.0 (27)
37		3.0 (33)	0.0 (33)

* A discordance of one category or more between 1st and 2nd determinations; Sample size shown in parentheses.

Table 7.5 Intra-observer error (% discordance) for scoring dental traits in Indians

Tooth	Trait	Full scoring*	Present/Absent
11 & 21	Winging	5.7 (53)	0.0 (53)
21	Shovelling	17.3 (52)	9.6 (52)
11		16.3 (49)	6.1 (49)
26	Carabelli trait	18.5 (54)	9.3 (54)
16		14.8 (54)	9.3 (54)
26	Metaconule (C5)	22.0 (50)	14.0 (50)
16		22.2 (45)	15.6 (45)
27	Hypocone reduction	6.5 (46)	2.2 (46)
17		4.7 (43)	2.3 (43)
43	Distal accessory ridge	18.9 (53)	18.9 (53)
33		15.1 (53)	13.2 (53)
45	Lingual cusp number	15.7 (51)	7.8 (51)
35		13.5 (52)	9.6 (52)
46	Protostylid	10.0 (50)	6.0 (50)
36		10.2 (49)	4.1 (49)
46	Deflecting wrinkle	27.3 (44)	4.5 (44)
36		20.0 (45)	4.4 (45)
46	Metaconulid	0.0 (51)	0.0 (51)
36		4.0 (50)	4.0 (50)
46	Entoconulid	10.6 (47)	10.6 (47)
36		14.6 (48)	14.6 (48)
47	Cusp number	11.1 (45)	8.9 (45)
37		11.6 (43)	11.6 (43)
47	Groove pattern	18.8 (48)	12.5 (48)
37		21.7 (46)	10.9 (46)

* A discordance of one category or more between 1st and 2nd determinations
Sample size shown in parentheses

Table 7.6 Intra-observer error (% discordance) for scoring dental traits in Jahai

Tooth	Trait	Full scoring*	Present/Absent
11 & 21	Winging	0.0 (18)	0.0 (18)
21	Shovelling	0.0 (11)	0.0 (11)
11		0.0 (12)	0.0 (12)
26	Carabelli trait	0.0 (18)	0.0 (18)
16		0.0 (18)	0.0 (18)
26	Metaconule (C5)	0.0 (13)	0.0 (13)
16		0.0 (12)	0.0 (12)
27	Hypocone reduction	0.0 (20)	0.0 (20)
17		0.0 (19)	0.0 (19)
43	Distal accessory ridge	11.8 (17)	0.0 (17)
33		11.8 (17)	0.0 (17)
45	Lingual cusp number	0.0 (19)	0.0 (19)
35		0.0 (18)	0.0 (18)
46	Protostylid	0.0 (14)	0.0 (14)
36		0.0 (16)	0.0 (16)
46	Deflecting wrinkle	0.0 (7)	0.0 (7)
36		0.0 (6)	0.0 (6)
46	Metaconulid	7.1 (14)	7.1 (14)
36		0.0 (17)	0.0 (17)
46	Entoconulid	0.0 (11)	0.0 (11)
36		0.0 (11)	0.0 (11)
47	Cusp number	0.0 (12)	0.0 (12)
37		0.0 (13)	0.0 (13)
47	Groove pattern	0.0 (11)	0.0 (11)
37		0.0 (10)	0.0 (10)

* A discordance of one category or more between 1st and 2nd determinations
Sample size shown in parentheses

Table 7.7 Tests of bilateral symmetry for 12 crown traits using graded-scale data in Malays (pooled-sex data)

Traits	Tooth	N	n	% symmetry	A-A	% symmetry (A-A excluded)	Spearman rho **	Fisher's P	Monte-Carlo 95% CI
Shovel	11, 21	266	13	95.1	5	95.0	0.91	0.000	
Carabelli	16, 26	275	45	83.6	42	80.7	0.81	0.000	0.00-0.011
Metaconule	16, 26	223	40	82.1	84	71.2	0.82	0.000	0.00-0.013
Hypocone reduction	17, 27	231	31	86.6	-	-	0.88	0.000	0.00-0.013
Distal accessory ridge	33, 43	278	41	85.3	178	59.0	0.68	0.000	
Lingual cusp number	35, 45	263	42	84.0	-	-	0.63	0.000	
Protostylid	36, 46	248	31	87.5	116	76.5	0.80	0.000	
Deflecting wrinkle	36, 46	159	37	76.7	82	51.9	0.61	0.000	
Metaconulid	36, 46	258	11	95.7	241	35.3	0.50	0.000	
Entoconulid	36, 46	244	14	94.3	183	77.0	0.85	0.000	
Cusp number	37, 47	232	33	85.8	-	-	0.82	0.000	
Groove pattern	37, 47	223	51	77.1	-	-	0.63	0.000	

N, sample size; n, number of cases with one or more grade differences; A-A, absence-absence pairs; Fisher's, Fisher's exact test; 95% CI, 95% confidence interval; *, $p<0.05$; **, $p<0.01$

Table 7.8 Tests of bilateral symmetry for 12 crown traits using graded-scale data in Chinese (pooled-sex data)

Traits	Tooth	N	n	%symmetry	A-A	% symmetry (A-A excluded)	Spearman rho **	Fisher's P	chi-square P
Shovel	11, 21	170	16	90.6	0	90.6	0.80	0.000	
Carabelli	16, 26	170	19	88.8	45	84.8	0.91	0.000	
Metaconule	16, 26	165	32	79.4	72	63.4	0.73	0.000	
Hypocone reduction	17, 27	127	20	84.3	-	-	0.82	0.000	
Distal accessory ridge	33, 43	165	30	81.8	107	48.3	0.56	0.000	
Lingual cusp number	35, 45	155	22	85.8	-	-	0.74	0.000	
Protostylid	36, 46	146	5	96.6	55	94.5	0.95		0.000
Deflecting wrinkle	36, 46	105	22	79.0	59	52.2	0.63	0.000	
Metaconulid	36, 46	167	6	96.4	154	53.8	0.76	0.000	
Entoconulid	36, 46	161	14	91.3	118	67.4	0.77	0.000	
Cusp number	37, 47	132	22	83.3	-	-	0.78		0.000
Groove pattern	37, 47	132	28	78.8	-	-	0.63	0.000	

N, sample size; n, number of cases with one or more grade differences; A-A, absence-absence pairs; Fisher's, Fisher's exact test; *, $p<0.05$; **, $p<0.01$

Table 7.9 Tests of bilateral symmetry for 12 crown traits using graded-scale data in Indians (pooled-sex data)

Traits	Tooth	N	n	% symmetry	A-A	% symmetry (A-A excluded)	Spearman rho **	Fisher's P	Monte-Carlo 95% CI	chi-square P
Shovel	11, 21	218	7	96.8	8	96.7	0.93	0.000		
Carabelli	16, 26	238	45	81.1	31	78.3	0.73	0.000	0.00-0.013	
Metaconule	16, 26	204	38	81.4	59	73.8	0.83	0.000		
Hypocone reduction	17, 27	192	29	84.9	-	-	0.83	0.000		
Distal accessory ridge	33, 43	230	22	90.4	174	60.7	0.71	0.000		
Lingual cusp number	35, 45	235	37	84.3	-	-	0.74			0.000
Protostylid	36, 46	227	16	93.0	155	77.8	0.88	0.000		
Deflecting wrinkle	36, 46	196	25	87.2	113	69.9	0.78	0.000		
Metaconulid	36, 46	235	14	94.0	211	41.7	0.76	0.000		
Entoconulid	36, 46	218	11	95.0	165	79.2	0.87	0.000		
Cusp number	37, 47	188	14	92.6	-	-	0.84	0.000		
Groove pattern	37, 47	206	48	76.7	-	-	0.68			0.000

N, sample size; n, number of cases with one or more grade differences; A-A, absence-absence pair; Fisher's, Fisher's exact test;*, $p<0.05$; **, $p<0.01$; 95% CI, 95% confidence interval

Table 7.10 Tests of bilateral symmetry for 12 crown traits using graded-scale in Jahai (pooled-sex data)

Traits	Tooth	N	n	% symmetry	A-A	% symmetry (A-A excluded)	Spearman rho **		Fisher's P
Shovel	11, 21	46	0	100.0	0	100.0	1.00	**	0.000
Carabelli	16, 26	46	10	78.3	3	76.7	0.81	**	0.000
Metaconule	16, 26	36	11	69.4	10	57.7	0.62	**	0.000
Hypocone reduction	17, 27	54	4	92.6	1	92.5	0.80	**	0.000
Distal accessory ridge	33, 43	53	5	90.6	37	68.8	0.75	**	0.000
Lingual cusp number	35, 45	59	8	86.4	-	-	0.43	**	0.020
Protostylid	36, 46	37	3	91.9	28	66.7	0.73	**	0.000
Deflecting wrinkle	36, 46	19	0	100.0	16	100.0	1.00	**	0.000
Metaconulid	36, 46	43	2	95.3	38	60.0	0.75	**	0.000
Entoconulid	36, 46	31	6	80.6	21	40.0	0.53	**	0.0036
Cusp number	37, 47	41	5	87.8	-	-	0.77	**	0.000
Groove pattern	37, 47	35	11	68.6	-	-	0.36		0.231

N, sample size; n, number of cases with one or more grade differences; A-A, absence-absence pair; Fisher's, Fisher's exact test; *, $p<0.05$; **, $p<0.01$

Table 7.11 Descriptive statistics for 13 dental crown trait using graded-scale data frequencies of occurrence (pooled-sex data)

		Ethnic group							
		Malays		Chinese		Indians		Jahai	
		count	%	count	%	count	%	count	%
Winging on upper central incisors	Winging	27	9.3	27	15.3	9	3.7	13	22.0
	Unilateral	15	5.2	17	9.7	17	7.0	6	10.2
	Straight and counterwinging	247	85.5	132	75.0	218	89.3	40	67.8
	Total	289	100	176	100	244	100	59	100
Shovelling on the upper central incisor	Absent	5	1.8			9	3.7	4	7.8
	Trace	155	56.0	42	24.4	172	71.4	36	70.6
	Semi-shovel	115	41.5	127	73.8	59	24.5	11	21.6
	Shovelling	2	0.7	3	1.7	1	0.4		
	Total	277	100	172	100	241	100	51	100
Carabelli trait on the upper first molar	Absent	45	15.5	47	26.7	35	14.1	9	14.3
	Pit and furrow	34	11.7	18	10.2	49	19.7	9	14.3
	Tubercle	186	64.1	100	56.8	154	61.8	36	57.1
	Free cusp	25	8.6	11	6.3	11	4.4	9	14.3
	Total	290	100	176	100	249	100	63	100
Metaconule on the upper first molar	Absent	111	40.2	76	42.9	62	26.2	16	29.6
	Weak cuspule	85	30.8	46	26.0	102	43.0	26	48.1
	Small cuspule	68	24.6	49	27.7	63	26.6	11	20.4
	Small moderate cusp	12	4.3	6	3.4	10	4.2	1	1.9
	Total	276	100	177	100	237	100	54	100

Table 7.11 (continued)

		Ethnic group							
		Malays		Chinese		Indians		Jahai	
		count	%	count	%	count	%	count	%
Hypocone reduction on the upper second molar	Absent	50	19.1	29	19.9	78	35.0	4	6.5
	Cuspule	11	4.2	7	4.8	12	5.4		
	Reduced	155	59.2	96	65.8	100	44.8	33	53.2
	Large	46	17.6	14	9.6	33	14.8	25	40.3
	Total	262	100	146	100	223	100	62	100
Distal accessory ridge on the lower canine	Absent	188	64.8	113	64.2	185	75.5	40	66.7
	Weak	94	32.4	60	34.1	57	23.3	20	33.3
	Strong	8	2.8	3	1.7	3	1.2		
	Total	290	100	176	100	245	100	60	100
Lingual cusp number on the lower second premolar	One	60	21.1	46	26.7	69	27.8	7	10.6
	Two	212	74.6	116	67.4	159	64.1	57	86.4
	Three	11	3.9	10	5.8	20	8.1	2	3.0
	Four	1	0.4						
	Total	284	100	172	100	248	100	66	100
Protostylid on the lower first molar	Absent	130	46.1	57	34.8	168	68.0	35	68.6
	Weak	11	3.9	17	10.4	8	3.2	2	3.9
	Strong	141	50.0	90	54.9	71	28.7	14	27.5
	Total	282	100	164	100	247	100	51	100

Table 7.11 (continued)

		Ethnic group							
		Malays		Chinese		Indians		Jahai	
		count	%	count	%	count	%	count	%
Deflecting wrinkle on the lower first molar	Absent	123	52.1	86	57.7	132	56.9	23	88.5
	Weak	80	33.9	35	23.5	77	33.2	2	7.7
	Strong	33	14.0	28	18.8	23	9.9	1	3.8
	Total	236	100	149	100	232	100	26	100
Metaconulid on the lower first molar	Absent	268	93.4	164	92.7	221	89.5	49	89.1
	Weak	18	6.3	7	4.0	16	6.5	4	7.3
	Strong	1	0.3	6	3.4	10	4.0	2	3.6
	Total	287	100	177	100	247	100	55	100
Entoconulid on the lower first molar	Absent	209	74.4	127	71.8	181	75.7	29	67.4
	Weak	68	24.2	45	25.4	55	23.0	12	27.9
	Strong	4	1.4	5	2.8	3	1.3	2	4.7
	Total	281	100	177	100	239	100	43	100
Cusp number on the lower second molar	Four	127	47.7	59	38.1	166	76.5	29	60.4
	Five	117	44.0	73	47.1	48	22.1	17	35.4
	Six	22	8.3	23	14.8	3	1.4	2	4.2
	Total	266	100	155	100	217	100	48	100
Groove pattern on the lower second molar	Y	23	8.6	9	5.8	94	39.5	2	4.0
	Cruciform	160	60.2	92	59.0	117	49.2	37	74.0
	X	83	31.2	55	35.3	27	11.3	11	22.0
	Total	266	100	156	100	238	100	50	100

Table 7.12 Univariate ethnic group comparisons using dichotomous data

Trait	Dichotomy		Ethnic group					Pearson Chi-square		
			Malays	Chinese	Indians	Jahai	Total	Value	df	P
Winging on upper central incisors	Absent	Count	262	149	235	46	692	26.24	3	0.000
		%	90.7	84.7	96.3	78	90.1			
	Present	Count	27	27	9	13	76			
		%	9.3	15.3	3.7	22	9.9			
	Total	Count	289	176	244	59	768			
		%	100	100	100	100	100			
Shovelling on the upper central incisor	Absent	Count	160	42	181	40	423	116.4	3	0.000
		%	57.8	24.4	75.1	78.4	57.1			
	Present	Count	117	130	60	11	318			
		%	42.2	75.6	24.9	21.6	42.9			
	Total	Count	277	172	241	51	741			
		%	100	100	100	100	100			
Carabelli trait on the upper first molar	Absent	Count	45	47	35	9	136	13.63	3	0.003
		%	15.5	26.7	14.1	14.3	17.5			
	Present	Count	245	129	214	54	642			
		%	84.5	73.3	85.9	85.7	82.5			
	Total	Count	290	176	249	63	778			
		%	100	100	100	100	100			

Table 7.12 (continued)

Trait	Dichotomy		Ethnic group					Pearson Chi-square		
			Malays	Chinese	Indian	Jahai	Total	Value	df	P
Metaconule on the upper first molar	Absent	Count	111	76	62	16	265	16.77	3	0.001
		%	40.2	42.9	26.2	29.6	35.6			
	Present	Count	165	101	175	38	479			
		%	59.8	57.1	73.8	70.4	64.4			
	Total	Count	276	177	237	54	744			
		%	100	100	100	100	100			
Hypocone on the upper second molar	Absent or cuspule	Count	61	36	90	4	191	35.15	3	0.000
		%	23.3	24.7	40.4	6.5	27.6			
	Present	Count	201	110	133	58	502			
		%	76.7	75.3	59.6	93.5	72.4			
	Total	Count	262	146	223	62	693			
		%	100	100	100	100	100			
Distal accessory ridge on the lower canine	Absent	Count	188	113	185	40	526	8.92	3	0.030
		%	64.8	64.2	75.5	66.7	68.2			
	Present	Count	102	63	60	20	245			
		%	35.2	35.8	24.5	33.3	31.8			
	Total	Count	290	176	245	60	771			
		%	100	100	100	100	100			

Table 7.12 (continued)

Trait	Dichotomy		Ethnic group					Pearson Chi-square		
			Malays	Chinese	Indian	Jahai	Total	Value	df	P
Lingual cusp number on the lower second premolar	One	Count	60	46	68	7	181	10.12	3	0.018
		%	21.1	26.7	27.4	10.6	23.5			
	>one	Count	224	126	180	59	589			
		%	78.9	73.3	72.6	89.4	76.5			
	Total	Count	284	172	248	66	770			
		%	100	100	100	100	100			
Protostylid on the lower first molar	Absent	Count	130	57	168	35	390	54.49	3	0.000
		%	46.1	34.8	68	68.6	52.4			
	Present	Count	152	107	79	16	354			
		%	53.9	65.2	32	31.4	47.6			
	Total	Count	282	164	247	51	744			
		%	100	100	100	100	100			
Deflecting wrinkle on the lower first molar[o]	Absent	Count	203	121	209	25	558	8.35	3	0.039[F]
		%	86	81.2	90.1	96.2	86.8			
	Present	Count	33	28	23	1	85			
		%	14	18.8	9.9	3.8	13.2			
	Total	Count	236	149	232	26	643			
		%	100	100	100	100	100			

Table 7.12 (continued)

Trait	Dichotomy		Ethnic group					Pearson Chi-square		
			Malays	Chinese	Indian	Jahai	Total	Value	df	P
Metaconulid on the lower first molar[1]	Absent	Count	268	164	221	49	702	3.35	3	0.340[F]
		%	93.4	92.7	89.5	89.1	91.6			
	Present	Count	19	13	26	6	64			
		%	6.6	7.3	10.5	10.9	8.4			
	Total	Count	287	177	247	55	766			
		%	100	100	100	100	100			
Entoconulid on the lower first molar	Absent	Count	209	127	181	29	546	1.79	3	0.617
		%	74.4	71.8	75.7	67.4	73.8			
	Present	Count	72	50	58	14	194			
		%	25.6	28.2	24.3	32.6	26.2			
	Total	Count	281	177	239	43	740			
		%	100	100	100	100	100			

Table 7.12 (continued)

Trait	Dichotomy		Ethnic group					Pearson Chi-square		
			Malays	Chinese	Indian	Jahai	Total	Value	df	P
Cusp number on the lower second molar	Four	Count	125	58	166	29	378	68.53	3	0.000
		%	47	37.4	76.9	60.4	55.2			
	> Four	Count	141	97	50	19	307			
		%	53	62.6	23.1	39.6	44.8			
	Total	Count	266	155	216	48	685			
		%	100	100	100	100	100			
Groove pattern on the lower second molar	+ and X	Count	243	147	144	48	582	112.59	3	0.000
		%	91.4	94.2	60.5	96.0	82.0			
	Y	Count	23	9	94	2	128			
		%	8.6	5.8	39.5	4.0	18.0			
	Total	Count	266	156	238	50	710			
		%	100	100	100	100	100			

°, 1 cells (12.5%) have expected count less than 5. The minimum expected count is 3.44.

¹, 1 cells (12.5%) have expected count less than 5. The minimum expected count is 4.60.

Figure 7.2 Frequencies of occurrence of dental crown traits in four ethnic groups using dichotomous data

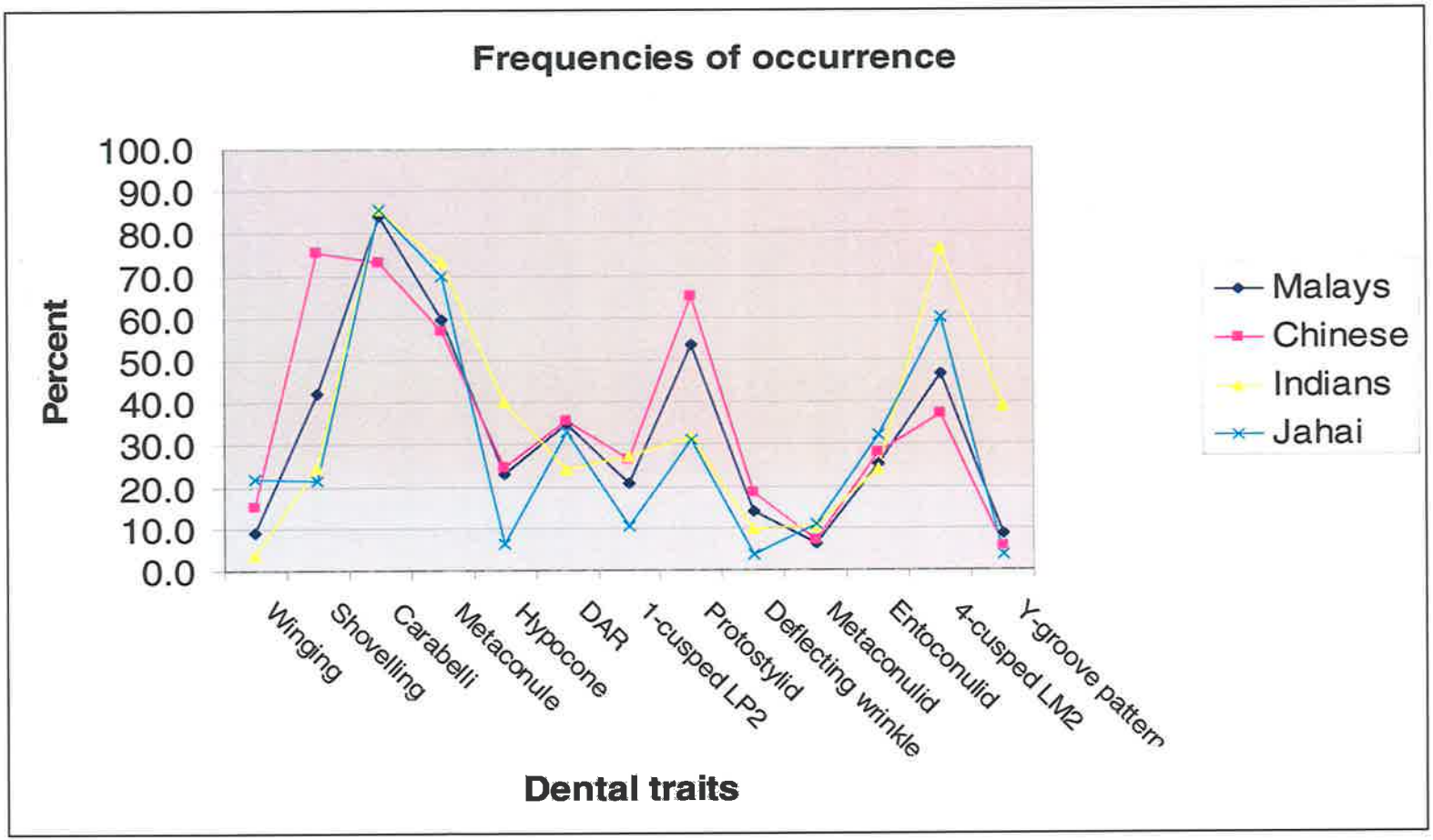


Table 7.13 Mean measure of divergence coefficients matrix

	Malays	Chinese	Indians	Jahai
Malays	-	0.068497	0.144152	0.074692
Chinese	0.000	-	0.319978	0.227152
Indians	0.000	0.000	-	0.186229
Jahai	0.000	0.000	0.000	-

Tests of significance in cells below diagonal

MMD coefficients in cells above diagonal

Figure 7.3 Dendrogram of four ethnic groups with sexes pooled

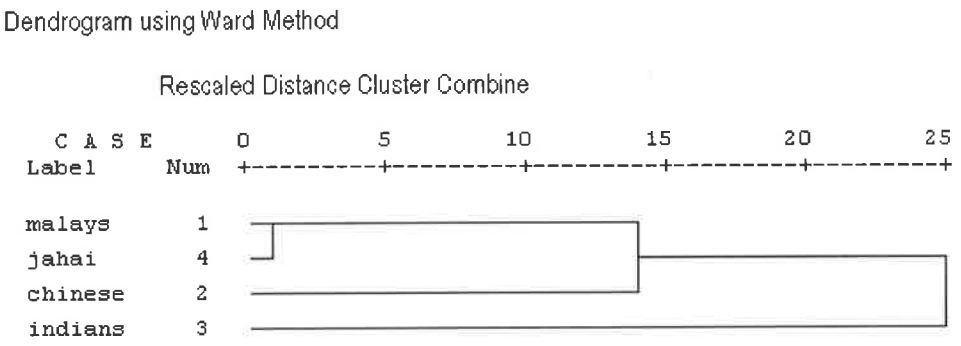
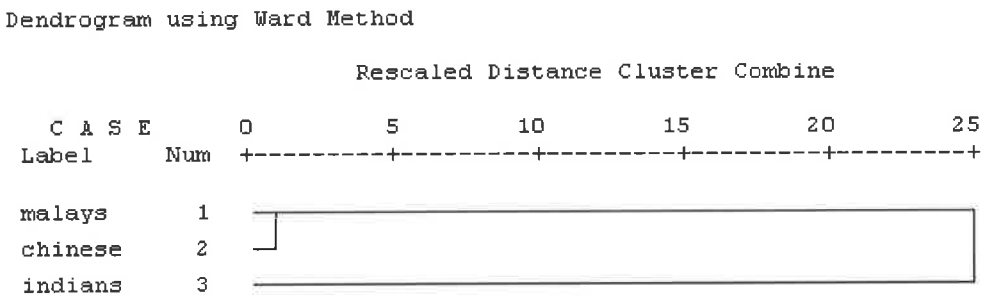


Figure 7.4 Dendrogram of three ethnic groups with sexes pooled



7.4 Discussion

The 13 dental traits scored in this study were representative of each tooth class and have been found to be suitable for population variation studies (Turner *et al.*, 1991). This suitability was based on several requirements, such as strong genetic influence on the ontogeny of the traits, low sexual dimorphism and strong symmetry (Tocheri, 2000).

Young participants in the study samples enable more effective analyses of dental crown features. The observation of dental traits on occlusal surfaces becomes very difficult if enamel is worn or affected with caries. Some difficulties in this respect were encountered in the Jahai sample, as many of the participants were from older age groups which resulted in the need to exclude some teeth from observations. The overall sample size of Jahai in this study was, therefore, small and the results for this group need to be interpreted with precaution.

Despite considerable time spent on training, the intra-observer error rate in this study was larger than those reported in other studies (Turner and Scott, 1977; Turner, 1987; Turner, 1990). This difficulty reflects the subjectivity involved in scoring methods for dental morphology. The categorical nature of the available scoring systems does not allow grading of the quasi-continuous spectra of tooth morphologies. For instance, the appearance of dental traits may fall between categories. Nichol and Turner (1986) indicated that if a discordance of more than two-grades occurred, and the presence-absence discordance was more than 10%, then problems exist in the scoring method. Comparing intra-observer error for full-graded scoring and presence-absence scoring between this study and that of Nichol and Turner (1986) revealed similar results for entoconulid, groove pattern, cusp number of lower second molar and hypocone reduction. My results indicated better reliability for scoring several traits including shovelling, Carabelli trait, distal accessory ridge, deflecting wrinkle, protostylid and lingual cusp number of lower second premolar, whereas results for the metaconule and winging were slightly better in the study by Nichol and Turner (1986). Difficult traits to score consistently in the three major ethnic groups were the metaconule and distal accessory ridge using dichotomous categories. This study confirmed, as one would expect, that dichotomous data display better reliability, as quantified by concordance rates, than full-graded scoring methods. Consistent with those results, Palomino *et al.* (1977) indicated their preference for using dichotomous data rather than full-graded scoring methods that increase the likelihood of misclassification.

Significant sexual dimorphism (after Bonferroni's adjustment) was found for three traits in Chinese; cusp number on the lower second molar, Carabelli trait on the upper first molar and

distal accessory ridge on the canine, and for one trait in the Jahai; distal accessory ridge on the canine. The same trend was reported in Chapters 4 and 5, based on odontometric data, with the Chinese being the most sexually dimorphic. Detailed analyses of the size of the lower second molar, upper first molar and lower canine from Chapter 5, and the sexually dimorphic traits found on these teeth i.e. cusp number, Carabelli trait and distal accessory ridge, indicate a pattern of strong sexual dimorphism in the Chinese and Jahai groups. The mesiodistal diameter of the lower second molar, buccolingual diameter of the upper first molar and the mesiodistal diameter of lower canine were ranked 1, 2 and 3 respectively for sexual dimorphism in Chinese and the mesiodistal diameter of the lower canine in the Jahai was ranked 1. In a previous study, Scott (1977b) noted the relationship in sexual dimorphism between ridge expression and canine dimension. Noss *et al.* (1983a) added that morphological (distal accessory ridge and Carabelli trait) sexual dimorphism was strongly influenced by tooth size dimorphism.

Overall, morphological traits were not as sexually dimorphic as tooth size variables. From 13 morphological variables in the four groups, only four were significant. One of the four variables, the four-cusped lower second molar, was more common in female Chinese, Similarly, Scott and Turner (1997) indicated that sexual dimorphism does not necessarily favor males. The distal accessory ridge was found more often in Chinese and Jahai males, which is consistent with Scott (1977b) who studied the frequencies and degrees of expression of the distal accessory ridge in seven ethnic groups in the United States of America. Carabelli trait in Malaysian Chinese was more common in males which is a similar result to that reported in Japanese and Chinese samples (Iwai-Liao *et al.*, 1996), Southern Chinese (Hsu *et al.*, 1999), Australian Aborigines (Townsend and Brown, 1981) and Indian Jats (Kaul and Prakash, 1981). In contrast, Hanihara (1977), Turner and Hanihara (1977), Scott (1980), Manabe *et al.* (1992) and Rusmah (1992) did not find any sexual dimorphism in the occurrence of this trait.

In essence, the amount of sexual dimorphism varies with different populations. In this study, sexual dimorphism could only be detected in Chinese and Jahai. It is likely that the scoring method may also contribute to differences in results from different studies.

Bilateralism was expressed equally in males and females for all ethnic groups. This result justified combining males and females for subsequent asymmetry/symmetry analysis. The frequencies of occurrence and degrees of expression of most traits showed significant symmetry, reflecting common developmental control for both sides of the dentition (Potter *et al.*, 1976). Exceptions were lingual cusp number and groove pattern in Jahai (Garn *et al.*, 1966a) suggesting caution is needed in using dental traits observed on the distal tooth of a

series because these teeth showed evidence of higher asymmetry. However, these traits are useful to comparing trait simplification between groups. Two significant variables from a total of 52 comparisons may represent a chance result (5%), therefore, subsequent analysis for ethnic comparisons utilized individual counts as this assumes an individual has a single genotype for any given trait. This simplifies the analysis without neglecting the importance of the underlying genotype.

There were several interesting findings that were similar to those of previous studies in other populations. Percentages of symmetrical expression were generally higher than 75% for the majority of traits, a result similar to those of Harris and Bailit (1980) and Noss *et al.* (1983b). When absence-absence pairs were excluded from the analysis, symmetry percentages were reduced (Mayhall and Saunders, 1986) especially for traits displaying low frequencies of occurrence (Townsend *et al.*, 1990). Two traits in Jahai did not exhibit significant symmetry and were associated with moderate-low correlations which is in contrast to the results of Baume and Crawford (1979) who reported strong correlations but non-significant symmetry in Mexican and Belizean populations. Several traits showed high symmetry but the values of correlation coefficients were not consistently high. However, percentages of concordance between sides, when absent-absent pairs were excluded, paralleled the values of correlation coefficients. Excluding absent-absent pairs is thought to reduce bias in the analysis (Townsend *et al.*, 1990).

Assessment of asymmetry for each grade revealed large discordance for several traits, ranging from absence on one side to maximum expression on the antimeric tooth. This occurred infrequently and to varying degrees among the four ethnic groups. Two traits consistently showed large discordances in the four ethnic groups; deflecting wrinkle and protostylid. There were three traits, shovelling, Carabelli trait and distal accessory ridge, which were consistently free from large discordances in all four ethnic groups. In conclusion, the present findings support the premise of common genetic control on both sides of the dentition with environmental influences causing minor deviation from perfect symmetry. This means that replacement of missing values with antimeric values is biologically and statistically acceptable.

There has been considerable discussion about racial dental complexes including those for Mongoloid, Caucasoid and Australoid groups. For each ethnic group in this study, it was decided to compare their dental characteristics with the racial dental complex models. Hanihara's (1968) Mongoloid dental complex identifies four traits, UI1 and UI2 shovelling, deflecting wrinkle, protostylid and metaconule. In my samples, the observed dental traits

generally conformed with the accepted models except for the metaconule, for which the Indian sample displayed the highest frequency compared with Malays, Chinese and Jahai.

According to Turner's Mongoloid dichotomy (Turner, 1990), four crown traits separate Sinodonts from Sundadonts. Shovelling, double shovelling and deflecting wrinkle are high in Sinodonts while 4-cusped lower second molar are common in Sundadonts. Jahai and Malays fitted the Sundadont description, while Chinese showed the Sinodont crown trait pattern.

Tratman (1950) described Indians as Indoeuropeans who frequently exhibit Carabelli trait, and the Malays and Chinese as Mongoloids who show high frequencies of shovelling, double shovelling, entoconulid and more complex occlusal surfaces. In my study, findings for Malays, Chinese and Jahai were consistent with Tratman's comments but Carabelli trait, entoconulid and double shovelling were not. Double shovelling was not scored in this study. The entoconulid did not provide statistically significant discrimination in the present study, although Indians had the lowest relative frequency.

It is worth discussing the value of Carabelli trait as a racial marker. The frequencies of Carabelli trait found in my sample were generally high when compared with other published material for Mongoloid populations (Rusmah, 1992; Iwai-Liao *et al.*, 1996; Hsu *et al.*, 1999). Only one article about Wainwright Eskimos by Hershey (1979) provides figures that approximate those obtained for Carabelli trait in this study. Hershey found a 92% frequency of occurrence for Carabelli trait while in my Mongoloid sample the frequency was around 75%-85%. An unexpected trend was found in the cuspal category (maximum expression for Carabelli trait). According to Tratman (1950), Indians should have a high frequency of Carabelli cusp but in my study they actually recorded the lowest frequency of 4.4% only. Several other researchers including Kraus (1959), Hershey (1979), Mayhall *et al.* (1982), and Mayhall (1999) have opined that only the Carabelli cusp (maximum category) provides discrimination between Caucasoid and Mongoloid groups. In fact, they suggested that the pit and intermediate categories occurred more frequently in Mongoloid populations. In this Malaysian sample, total frequencies of occurrence of Carabelli trait only discriminate Chinese from the other three groups but they failed to have any discriminating power for Malays, Jahai and Indians. This result raises doubt about the role of Carabelli trait as a Caucasoid trademark.

The characteristics of the Indian sample generally reveal less complex occlusal and palatal surfaces, consistent with Tratman's (1950) anatomical descriptions of his sample, and partially compatible the Caucasoid dental complex of Mayhall *et al.* (1982). From six dental traits proposed by Mayhall *et al.* (1982), only two traits, low prevalence of shovel and high prevalence of hypocone reductions, fit the Indian dental characteristics found in this study.

The Jahai, who represent Negritos from the Malaysian Peninsula, have a similar pattern of dental characteristics as the Aetas from the Philippines (Hanihara, 1992). The similarities noted include low frequencies of shovelling, deflecting wrinkle, and high frequencies of 4-cusped lower second molars.

In summary, the analyses performed in this Chapter indicate that there are two main groups based on, dental traits, in the Malaysian sample. The Mongoloid group comprises Malays, Negritos (Jahai) and Chinese, whereas the Indian sample can be classified as Indoeuropean (Indian). The Mongoloid group can be further subdivided, with the Jahai and Malays fitting the Sundadont profile and the Chinese conforming to a Sinodont profile, as described by Turner (1990).

Population affinities using multivariate analyses of non-metric dental data yielded different outcomes for the Jahai than those based on metric dental data. Similarly, Hanihara (1976) found different results for Australian Aborigines between analyses based on metric compared with non-metric data. Unfortunately, he was not able to provide an explanation for this discrepancy. In contrast, Matsumura and Hudson (2005) used both data types to investigate South East Asian population history and their results were remarkably consistent. However, the results for Negritos (Philippine Aetas) in their study, were also found to differ for metric and non-metric data. In their report on phenetic distance, the Negritos were placed between Australomelanesians and East Asians (in fact closer to South East Asians) based on non-metric data. However, the results of metric analyses indicated that the Negritos were similar to Sinodonts. These researchers speculated that, based on their results, the Negritos could be descendants of a population with Australomelanesian traits but some mixture with Sinodonts. In my study, comparisons were limited to those between only four modern Malaysian populations and so no firm conclusions about the position of the Negrito sample in relation to other groups can be made.

Nevertheless, the non-metric data for the Jahai led to findings that are explainable and widely accepted in relation to their ethnic affinities. The non-metric dental data would seem to be more reliable for assessing population affinities than tooth size data.

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Chapter 8 Morphological variation in dental crowns for human identification

8.1 Introduction

For many decades, anthropologists and forensic scientists have used biological evidence such as cranial morphology (Giles and Elliot, 1962; Gill, 1986), deoxyribonucleic nucleic acid profiling (Ayres *et al.*, 2002) and dental features (Matis and Zwemer, 1971; Haeussler *et al.*, 1989; Lease and Sciulli, 2005) to reconstruct human identity. An important aspect of reconstructing identity is to determine the ethnicity of the unknown human remains, as many other parameters depend on ethnicity.

In 2004 and 2005, the world experienced major disasters that resulted in the loss of many thousands of lives, and caused billion of dollars worth of damage. Natural disasters like the tsunami in the South East Asia, the tropical cyclone in America, and most recently an earthquake in Kashmir, have left enormous problems for governments in terms of infrastructure, economics, health care, and the large number of unidentified bodies. The unidentified bodies from the Asian Tsunami in Banda Aceh were disposed by mass burial, a practice which is not accepted by some communities. Conversely, unidentified bodies in Phuket, Thailand, believed to be Europeans, Japanese, Australians, and local Thai and Burmese, are still in the process of being formally identified.

Identification processes utilize three main comparative methods: DNA, fingerprints and dental records. Comparative identification processes are not possible in situations where ante-mortem records are not readily available. In these situations, reconstructive identification becomes important to refine the search for potential ante-mortem records. In examples like a homicide case, where the body of the victim has been concealed for some time, or suicide bombers in man-made disasters, reconstructive identification may provide clues leading to confirmation of identity. The identity of a homicide victim or a suicide bomber may provide further evidence which identifies the perpetrator or mastermind behind the crime. Without an identity, a case may remain unsolved for a considerable period of time.

Dental morphological variations have been used in anthropology and archaeology for personal characterization and population affinity (Scott and Turner, 1997). In the context of legal requirements, any estimation of ethnicity should be based on objective and sound scientific evidence. Moreover, the methods should be accepted and practised by the forensic community, and they should provide acceptable precision or error rate (Daubert, 1993).

In this chapter, the possibility of analyzing dental traits using logistic regression analysis for ethnicity estimation will be explored. The aim is to identify those dental traits that provide best discrimination and to generate prediction models that fulfill legal requirements and are practical to be used in forensic situations in Malaysia.

8.2 Materials and methods

723 subjects (excluding Jahai) were included in this analysis with 682 in the main sample and 41 reserved for a test sample. Table 8.1 shows the original sample distribution according to sex and age for each ethnic group. Table 8.2 shows the distribution of Mongoloids and Indians comprising individuals with complete data sets suitable for multivariate analysis. From 682 subjects, 401 were available for analysis using logistic regressions. Table 8.3 provides the summary of trait classifications and the breakpoints for dichotomous data. The majority of the crown trait classifications, except for entoconulid, Carabelli trait and groove pattern, were simplified from the Arizona State University (ASU) systems (Turner *et al.*, 1991). The ASU standard plaques were used for all traits to provide added guidance. The classification of Townsend *et al.* (1990) was adopted for the entoconulid, as it included scoring for four-cusped molars, whereas the ASU system only scored the entoconulid on five-cusped molars. Carabelli trait was scored using Dahlberg's plaque P12A, and groove pattern was assessed using plaque P10 (Dahlberg, 1956).

Analyses were conducted to compare Mongoloid and Indian samples only. The Mongoloid sample consisted of Malays and Chinese with sexes pooled. In Chapter 7 it was shown that the dental traits analysed did not exhibit significant sexual dimorphism, hence combining sexes was considered to be acceptable. The decision to combine Malays and Chinese was based on ethnic group affinities evaluated in Chapter 7. The inclusion of Jahai was thought to complicate the analyses, so this group was not included in this chapter. The frequencies of dental traits, as shown in Figure 7.2 in Chapter 7, indicated that the profile of the Jahai was similar to Malays but overlapped with other groups. Another reason for their exclusion was the contradictory situation of the Jahai's affinity from odontometric analysis (Chapter 4) compared with that found in Chapter 7 using morphological data.

For an ethnic prediction model, logistic regression was chosen because the response (dependent) variable, namely ethnicity, is binary (Mongoloid or Indian) and the explanatory variables, dental morphological traits, are categorical. Logistic regression does not require the explanatory variables to be normally distributed, linearly related or to exhibit equally distributed variance across dependent variables, unlike discriminant function analysis.

The logistic regression model can be written as:

$$p_a = \frac{\exp (B_o + B_1x_1 + \ldots + B_q x_q)}{1 + \exp (B_o + B_1x_1 + \ldots + B_q x_q)}$$

where p_a refers to the probability of being Indian while p_0, the probability of being Mongoloid can be written as follows:

$$p_0 = \frac{1}{1 + \exp (B_o + B_1x_1 + \ldots + B_q x_q)}$$

B_0 refers to constant with the coefficients B_q estimated by maximum likelihood.

The most discriminative dental traits were selected using the forward stepwise selection method with entry testing based on the significance of the score statistic, and removal testing based on the probability of a likelihood-ratio statistic based on the maximum partial likelihood estimates (SPSS release 11.0.1 2001).

Classification of individuals into groups can then be performed on the basis of individual's scores (Lease and Sciulli, 2005) as follows:

Predicted probability = Constant + Σ B_ix_i

B, coefficients of regression; x, score on the dental traits

Predicted group membership was determined by the cutting score of zero. A positive value of predicted probability was assigned as being Indian, whereas Mongoloids took negative values. The predicted group membership was compared with true group membership. The performance of classification was presented in a classification table. The proportion criterion and Press's Q statistic were used to assess the validation of classification performance. The proportion chance criterion formula is as follows:

$C_{PRO} = p^2 + (1-p)^2$

C_{PRO} = The proportion chance criterion

p = Proportion of case in group 1

1-p = Proportion of case in group 2

Press's Q statistic was based on the total sample size, number of correct classifications and number of groups involved. The calculated value was then compared with a critical value of 3.84 (derived from a chi-square table with one degree of freedom and alpha at 5% level). If the calculated Q value was larger than the critical value, the predictions were considered to be better than chance. The formula for Press's Q value is as follows:

$$\text{Press's Q} = \frac{(N-(n*K))^2}{N(K-1)}$$

N = Total sample size

n = Number of observations correctly classified

K = Number of groups

Table 8.1 Distribution of ethnic group according to sex and age

Ethnic group	Sex	N	Mean (years)	SD
Malays	Females	167	15.6	1.2
	Males	126	15.1	1.3
	Total	293	15.4	1.3
Chinese	Females	88	14.5	1.3
	Males	90	14.7	1.5
	Total	178	14.6	1.4
Indian	Females	131	15.8	1.4
	Males	121	15.6	1.3
	Total	252	15.7	1.3

N, sample size; SD, standard deviation

Table 8.2 Distribution of Mongoloid and Indian samples with complete data

Ethnicity		Sex		Total
		Females	Males	
Mongoloids	Count	138	117	255
	%	54.1	45.9	100.0
Indians	Count	76	70	146
	%	52.1	47.9	100.0
Total	Count	214	187	401
	%	53.4	46.6	100.0

Table 8.3 Summary of dental crown trait classifications

Traits	Tooth	Classification	ASU grade	Score	Breakpoint for dichotomous data
Winging	11,21	Bilateral winging	1	1	1-present
		Unilateral winging	2	2	23-absent
		Counter wing and straight	3,4	3	
Shovel	11,21	Absent	0	0	01-absent
		Trace	12	1	23-present
		Semi	34	2	
		Shovel	56	3	
Metaconule	16,26	Absent	0	0	0-absent
		Weak cuspule	12	1	123-present
		Small cuspule	3	2	
		Small/moderate cusp	45	3	
Carabelli trait*	16,26	Absent	a	0	0-absent
		Pit & furrow	bc	1	123-present
		Tubercle	defg	2	
		Cusp	h	3	
Hypocone	17,27	Absent/ridge	0 1	0	01-absent
		Cuspule	2	1	23-present
		Reduced cusp	34	2	
		Large	56	3	
Distal accessory ridge	33,43	Absent	0	0	0-absent
		Weak	12	1	12-present
		Strong	345	2	

Table 8.3 (continued)

Traits	Tooth	Classification	ASU grade	Score	Breakpoint for dichotomous data
Lingual cusp number	35,45	One		1	1-one cusp
		Two		2	234-not one cusp
		Three		3	
		Four		4	
Protostylid	36,46	Absent	0	0	0-absent
		Weak	123	1	12-present
		Strong	4567	2	
Metaconulid	36,46	Absent	0 1.5	0	0-absent
		Small	123	1	12-present
		Large	4	2	
Entoconulid	36,46	Absent	0	0	0-absent
		Weak	12	1	12-present
		Strong	34	2	
Deflecting wrinkle	36,46	Absent	0 1	0	01-absent
		Weak	2	1	2-present
		Strong	3	2	
Cusp number	37,47	Four		4	4-four cusp
		Five		5	56-not four cusp
		Six		6	
Groove pattern^	37,47	Y	Y	1	1-Y pattern
		+	+	2	23-+, X pattern
		X	X	3	

^ observation using Dahlberg plaque P10 * observation using Dahlberg plaque P12A

8.3 Results

Table 8.4 shows similarities in the profile of frequencies of occurrence of dental traits in Mongoloids and Indians obtained in this chapter with those reported Chapter 7. Mongoloids were characterized by high frequencies of winging, shovelling, and complex occlusal features on the lower molar, whereas Indians showed simpler and more reduced occlusal features of the distal molar teeth (except the upper first molar).

As a result of stepwise methods, three logistic regression models were identified as most discriminative (Table 8.5) from steps 1, 2 and 5. The model associated with step 1 comprised groove pattern on the lower second molar; the model from step 2 comprised groove pattern and molar cusp number, and the model from step 5 comprised shovelling, metaconule, protostylid, second molar cusp number and groove pattern (Table 8.5). The models from steps 1, 2 and 5 were significant (chi-square (1) = 75.96, $p<0.000$ for step 1; chi-square (2) = 120.68 for step 2 and chi-square (5) =159.53, $p<0.000$ for step 5). Cox and Snell tests revealed step 1 explained 17% of variance in the dependent (ethnicity) variables, step 2 explained 26% and step 5 explained 33%.

The best performances from step 1, 2 and step 5 were 75.1% and 78.3% for original sample and 78.9% and 73.7% for the test samples (Table 8.6). Both original and test samples performed better than chance, yielding significance at $p<0.05$ in step 1 and step 5. Press's Q (1) original sample = 100.8, $p<0.000$ and Press's Q (1) test sample = 6.37, $0.01<p<0.02$ for step 1, while the Press's Q (1) original sample = 128.5, $p<0.000$ and Press's Q (1) test sample = 4.26, $p<0.05$ for step 2. The proportion criterion indicated that all logistic functions passed benchmarks for correct classification better than chance. The benchmark would be 53.7% for the original sample and 51.2% for the tests sample. Misclassification rates using the model from step 5 was similar in males and females for Mongoloids (15/31 females and 16/31 males) and Indians (26/56 females and 30/56 males). An example for using linear logistic regression analysis is given in an Appendix 8.1.

Table 8.4 Descriptive statistics for thirteen dental traits in Mongoloid and Indian samples with complete data

Traits		Ethnicity			
		Mongoloid	%	Indian	%
Winging on upper central incisors	Present	34	13.3	5	3.4
	Absent	221	86.7	141	96.6
Shovelling on the upper central incisor	Absent	123	48.2	117	80.1
	Present	132	51.8	29	19.9
Metaconule on the upper first molar	Absent	104	40.8	38	26.0
	Present	151	59.2	108	74.0
Carabelli trait on the upper first molar	Absent	52	20.4	24	16.4
	Present	203	79.6	122	83.6
Hypocone on the upper second molar	Absent or cuspule	64	25.1	63	43.2
	Present	191	74.9	83	56.8
Distal accessory ridge on the lower canine	Absent	162	63.5	109	74.7
	Present	93	36.5	37	25.3
Lingual cusp number on the lower second premolar	One	58	22.7	39	26.7
	More than one	197	77.3	107	73.3
Deflecting wrinkle on the lower first molar	Absent	213	83.5	132	90.4
	Present	42	16.5	14	9.6
Metaconulid on the lower first molar	Absent	238	93.3	132	90.4
	Present	17	6.7	14	9.6
Entoconulid on the lower first molar	Absent	192	75.3	113	77.4
	Present	63	24.7	33	22.6
Protostylid on the lower first molar	Absent	114	44.7	101	69.2
	Present	141	55.3	45	30.8
Cusp number on the lower second molar	Four	109	42.7	120	82.2
	More than four	146	57.3	26	17.8
Groove pattern on the lower second molar	+ and X	237	92.9	82	56.2
	Y	18	7.1	64	43.8

Table 8.5 Coefficient of regressions and model summary

	Coefficients of regression	B	S.E.	Cox & Snell R Square
Step 1	GZZA	2.32984	0.30	0.17
	Constant	-1.06134	0.13	
Step 2	C_N_ZA	-1.68812	0.27	0.26
	GZZA	2.18764	0.31	
	Constant	-0.42193	0.15	
Step 3	SZA	-1.18339	0.28	0.29
	C_N_ZA	-1.49546	0.28	
	GZZA	2.16709	0.32	
	Constant	-0.09082	0.17	
Step 4	SZA	-1.17316	0.29	0.31
	C5ZA	0.82791	0.28	
	C_N_ZA	-1.52385	0.28	
	GZZA	2.20253	0.32	
	Constant	-0.65553	0.26	
Step 5	SZA	-1.04966	0.29	0.33
	C5ZA	0.95462	0.29	
	PZA	-0.87188	0.27	
	C_N_ZA	-1.48236	0.29	
	GZZA	2.24243	0.33	
	Constant	-0.43735	0.27	

a, variables entered on step 1: GZZA; b, variable(s) entered on step 2: C_N_ZA; c, variable(s) entered on step 3: SZA; d, variable(s) entered on step 4: C5ZA; e, variable(s) entered on step 5: PZA

Abbreviations used: SZA, shovelling; C5ZA, metaconule; PZA, protostylid; C_N_ZA, cusp number on the lower second molar; GZZA, groove pattern.

Table 8.6 Classification matrix for logistic regression analysis

	Observed	Predicted					
		Selected Cases			Unselected Cases		
		Mongoloid	Indian	%	Mongoloid	Indian	%
Step 1	Mongoloid	237	18	92.9	8	0	100.0
	Indian	82	64	43.8	4	7	63.6
Overall Percentage				75.1			78.9
Step 2	Mongoloid	237	18	92.9	8	0	100.0
	Indian	82	64	43.8	4	7	63.6
Overall Percentage				75.1			78.9
Step 3	Mongoloid	240	15	94.1	8	0	100.0
	Indian	85	61	41.8	6	5	45.5
Overall Percentage				75.1			68.4
Step 4	Mongoloid	202	53	79.2	8	0	100.0
	Indian	43	103	70.5	6	5	45.5
Overall Percentage				76.1			68.4
Step 5	Mongoloid	224	31	87.8	8	0	100.0
	Indian	56	90	61.6	5	6	54.5
Overall Percentage				78.3			73.7

Some of the unselected cases are not classified due to missing values in the independent variables.

8.4 Discussion

Similarities in patterns of dental features with those reported in previous chapters confirmed the representativeness of the smaller subsample in this study. Thus, the omission of missing values did not change the composition of Mongoloid and Indian samples.

Only one study has been found which used logistic regression for ethnic prediction and that was only in primary teeth (Lease and Sciulli, 2005). The performances derived from their tests were outstanding, with discrimination success above 90% being reported between African-American and European-American children. Previous works e.g. Matis and Zwemer (1971) and Haeussler *et al.* (1989) concentrated on discriminant function analysis which required the data to meet strict statistical assumptions. Matis and Zwemer (1971) used both metric and non-metric data to predict ethnicity using discriminant function analysis. As non-metric, present/absent, data are distributed according to a binomial distribution, assumptions of normality could seriously bias their interpretations. Discriminant function analysis is considered not to be suitable to handle categorical data for analysis (Hair *et al.*, 1995).

Logistic regression was robust and provided regression functions that could be used for prediction, equivalent to discriminant function analysis products. From the analysis, the fifth step of the stepwise process showed the highest correlation with ethnicity prediction. Performance also improved with additional traits. Performance for ethnicity prediction using logistic regression was slightly better than for DFA reported in Chapter 6 using metric data (range from 68% to 77%). There were similarities in the teeth selected as the most discriminative in both DFA and logistic regression analysis. In DFA, the best discriminators from the pooled sex data consisted of eight tooth size measurements from maxillary incisor, canine, premolar and molar, and mandibular incisor, premolar and molar, whereas logistic regression identified five best discriminators representing maxillary incisor and molar, and mandibular molar. Considering the number of variables and the classification rate, the non-metric model scores seem to offer a more practical prediction option. Both prediction models can be used to complement each other, meaning that in a situation where obvious interproximal wear exists, we could opt for morphological traits, whereas in situations, where for example caries on the buccal pit eliminates the assessment of morphology but the tooth is suitable for tooth size measurement, we could opt for odontometric analysis.

Detailed analysis of each variable did, however, reveal some limitations in the practical application of the models. The regression model can only be used in an individual who has lower second molars erupted. Similarly, odontometric analysis utilized tooth size of the upper

second molar. Thus, these current models could only be reliably used for teenagers and older individuals. Future research should also consider tooth size and morphology of younger populations.

With around a 22% misclassification rate, the performance of the best logistic regression model was not as high as in previous publications (Matis and Zwemer, 1971; Lease and Sciulli, 2005). The level of misclassification suggests some possibility of admixture in ancestral populations. This is not unexpected as the small size of the Malaysian Peninsula and long history of immigration has been reported to produce ratios of 10 males to one female in Indian migrants as one example (Nagata, 1979).

In summary, morphological data provide better hit ratio performance than tooth size measurements in determining ethnicity of individuals and would appear to be suitable as an alternative approach to human identification in forensic situations.

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Chapter 9 Discrimination between different human ethnic groups using metric and non-metric dental data

9.1 Introduction

Studies of dental variation reported in Chapters 4 and 7, utilizing metric and non-metric data respectively, have shown that Malaysian populations were formed by two main ancestral backgrounds, Mongoloid and Indian. This is in accord with most of the anatomical descriptions of tooth morphology in these populations compiled before World War II (Tratman, 1950).

Prediction models derived from separate studies of metric and non-metric data presented in previous chapters were able to correctly estimate ethnicity with an accuracy in the range of 73% to 78%. The model using non-metric data provided slightly better success rates than that with metric data. Lease and Sciulli (2005) have also shown that non-metric data contributed better classification rates than metric data in their study of deciduous teeth. Interestingly, when they combined both metric and non-metric information, logistic regression models were able to successfully classify ethnicity over 90% of the time. Matis and Zwemer (1971) used metric and non-metric data from the permanent dentition of American populations for classification of American Indians and Eskimos. They successfully classified ethnicity in more than 90% of cases. Both of these studies presented results comparable with the craniometry study of Giles and Elliot (1962).

Similar studies have not previously been undertaken in Malaysian populations. The investigation reported in this chapter, therefore, aims to identify the most discriminative dental variables, both metric and non-metric, and to generate linear regression models that are reliable and practical for forensic applications.

9.2 Materials and methods

258 cases from the total of 790 were found to be suitable for analysis. Cases with missing values were omitted from this analysis. The sample distribution according to sex and ethnic group is presented in Table 9.1. Procedures for impressions and model casting adhered to manufacturer's instructions and clinical standards. Ancestry of participants was determined by interviews from parents. Only those who were "pure" for three generations were included in the analysis. Teeth with caries, restorations and wear were excluded. For tooth size abbreviations, please refer to Chapter 5.

Tooth size measurements based on the definitions of Moorrees (1957) and maximum mesiodistal (MD) and buccolingual (BL) diameters were measured using automatic digital calipers. The proportion of total variance due to measurement error was less than 3%, and no systematic bias was detected. Tooth size was measured on both sides of the arch, but data from the right side only were used for inter-population analyses. In cases where the right side tooth was missing or had been extracted, its antimere was used. For multivariate analyses, the missing values were replaced with group means.

Morphological observations utilized the Arizona State University (Turner *et al.*, 1991), Townsend *et al.* (1990) and Dahlberg (1956) scoring methods. Dichotomy breakpoints for 13 traits are presented in Table 9.2. Observations of morphological traits were presented as individual counts (Scott, 1977). Intra-observer error ranged from 0.0% to 18%. For the majority of traits the measurement error was less than 10%. Shovelling, metaconule and distal accessory ridge presented an error rate of more than 10% in Malays, Chinese and Indians.

Logistic regression was used to analyse the combination of the two types of data; categorical and continuous. The logistic regression models can be written as follows:

$$p_a = \frac{\exp (B_o + B_1x_1 + \ldots + B_q x_q)}{1 + \exp (B_o + B_1x_1 + \ldots + B_q x_q)}$$

where p_a represents the probability of being Indian

$$p_0 = \frac{1}{1 + \exp (B_o + B_1x_1 + \ldots + B_q x_q)}$$

where p_0 represents the probability of being Mongoloid

The most discriminative dental traits were selected using the backward stepwise selection method where variable removal was based on the probability of the likelihood-ratio

statistic based on the maximum partial likelihood estimates (SPSS release 11.0.1., 2001). The first step included all inputs in the block. At each subsequent step, the predictor that did not meet the criteria was omitted from the model. Stepwise removal probability was set at 0.10 as a default. Logistic regression treated all data as continuous unless categorically defined in the analysis. Logistic regression was considered to be suitable for the analysis since it is robust to non-normality, unequal variance across dependent variables and non-linearity. Two sets of variables were used for logistic regressions. First input used all variables, 28 metric and 13 non-metric. Second input used 20 metric variables; omitting incisor variables, and 13 non-metric variables.

Prediction of individuals into groups can then be performed on the basis of individual's scores (Lease and Sciulli, 2005) as follows:

Predicted probability = Constant + Σ $B_i x_i$

where B, coefficients of regression; x, score on the dental traits or tooth size measurements

Predicted group membership was determined by the cutting score of zero. A positive value of predicted probability was assigned as Indian, while Mongoloids took negative values. The predicted group membership was compared with true group membership. The performance of classification was presented in a classification table. The proportion criterion and Press's Q statistic were used to assess the validity of the classification performance. The proportion chance criterion, Cpro, formula is as follows:

$C_{PRO} = p^2 + (1-p)^2$

p = Proportion of case in group 1

1-p = Proportion of case in group 2

Press's Q statistic was based on total sample size, number of correct classifications and number of groups involved. The calculated value was then compared with a critical value of 3.84 (derived from a chi-square table with one degree of freedom and alpha at 5%). If the calculated Q value was larger than the critical value, the predictions were considered to be better than chance. The formula for Press's Q is as follows:

$$\text{Press's Q} = \frac{[N-(n*K)]^2}{N(K-1)}$$

N = Total sample size

n = Number of observations correctly classified

K = Number of groups

Descriptive statistics and multivariate analysis were analysed using SPSS release 12.0.1. and Microsoft office Excel program.

Table 9.1 Sample distribution for combined metric and non-metric data

Sex		Ethnicity		Total
		Mongoloid	Indian	
Females	Count	88	42	130
	%	53.0	45.7	50.4
Males	Count	78	50	128
	%	47.0	54.3	49.6
Total	Count	166	92	258
	%	100.0	100.0	100.0

Table 9.2 Sample distribution in test samples

Sex		Ethnicity		Total
		Mongoloids	Indians	
Females	Count	22	14	36
	%	44.9	58.3	49.3
Males	Count	27	10	37
	%	55.1	41.7	50.7
Total	Count	49	24	73
	%	100.0	100.0	100.0

Table 9.3 Crown trait classifications used in the study

Traits	Tooth	Classification	ASU grade	Score	Breakpoint for dichotomous data
Winging (WW)	11,21	Bilateral winging	1	1	1-present
		Unilateral winging	2	2	23-absent
		Counter wing and straight	3,4	3	
Shovel (SZ)	11,21	Absent	0	0	01-absent
		Trace	12	1	23-present
		Semi	34	2	
		Shovel	56	3	
Metaconule (C5Z)	16,26	Absent	0	0	0-absent
		Weak cuspule	12	1	123-present
		Small cuspule	3	2	
		Small/moderate cusp	45	3	
Carabelli trait* (CARA)	16,26	Absent	a	0	0-absent
		Pit & furrow	bc	1	123-present
		Tubercle	defg	2	
		Cusp	h	3	
Hypocone (HYP)	17,27	Absent/ridge	0 1	0	01-absent
		Cuspule	2	1	23-present
		Reduced cusp	34	2	
		Large	56	3	
Distal accessory ridge (DAR)	33,43	Absent	0	0	0-absent
		Weak	12	1	12-present
		Strong	345	2	

Table 9.3 (continued)

Traits	Tooth	Classification	ASU grade	Score	Breakpoint for dichotomous data
Lingual cusp number (1-LP2)	35,45	One		1	1-one cusp
		Two		2	234-not one cusp
		Three		3	
		Four		4	
Protostylid (PZ)	36,46	Absent	0	0	0-absent
		Weak	123	1	12-present
		Strong	4567	2	
Metaconulid (C7)	36,46	Absent	0 1.5	0	0-absent
		Small	123	1	12-present
		Large	4	2	
Entoconulid (C6)	36,46	Absent	0	0	0-absent
		Weak	12	1	12-present
		Strong	34	2	
Deflecting wrinkle (DW)	36,46	Absent	0 1	0	01-absent
		Weak	2	1	2-present
		Strong	3	2	
Cusp number (CN)	37,47	Four		4	4-four cusp
		Five		5	56-not four cusp
		Six		6	
Groove pattern^(Y-GP)	37,47	Y	Y	1	1-Y pattern
		+	+	2	23- +, X pattern
		X	X	3	

^ observation using Dahlberg plaque P10

9.3 Results

Table 9.1 shows approximately equal numbers of males and females in the samples for analysis. The total sample (331) was reduced from 790 because only cases with complete metric and non-metric data were included for subsequent analyses. 258 cases were used as the original sample to generate logistic regression models, while 73 additional cases were reserved as test cases to assess the validity of the logistic regression models (Table 9.2). Table 9.4 compares frequencies of occurrence of 13 dental morphological traits between Mongoloids and Indians. Winging, shovelling, DAR, and protostylid occurred more frequently in the Mongoloid sample, while Carabelli, metaconule, hypocone reduction, 4-cusped lower molars and Y-groove patterns were dominant in the Indian group. The other traits exhibited no frequency bias between the two ethnic groups. Table 9.5 shows that the majority of Mongoloid tooth sizes are larger than those of Indians, except the mesiodistal diameter of the upper second molar and several lower buccolingual dimensions.

Table 9.6 shows the classification rate between Mongoloids and Indians using 28 metric and 13 non-metric traits. Out of 26 logistic function models, only one achieved a classification success rate below 84.0%. The remaining functions performed well above 84.0% of average in both the original and test samples. Appendix 9.1 presents the coefficients of regression for each variable retained in the models. The backward stepwise method selected 26 models for ethnicity prediction. The minimum predictor variables for ethnicity prediction were 16 in step 26. All models included the lower central incisor, and the upper and lower second molar. Table 9.7 indicates that the classification rate for data input using 20 metric and 13 non-metric traits was generally as reliable as the model presented in Table 9.6.

All classification achievements were higher than 87.0% in the original sample and 79.5% in the test sample. Press's Q statistics and proportion chance criterion confirmed that all classifications were better than expected by chance.

Table 9.4 Descriptive statistics for 13 non-metric traits in Mongoloids and Indians

Dental traits		Ethnicity				
		Mongoloid	%	Indian	%	Total
Winging on upper central incisors	Present	24	14.5	2	2.2	26
	Absent	142	85.5	90	97.8	232
	Total	166	100.0	92	100.0	258
Shovelling on the upper central incisor	Absent	75	45.2	81	88.0	156
	Present	91	54.8	11	12.0	102
	Total	166	100.0	92	100.0	258
Carabelli trait on the upper first molar	Absent	38	22.9	13	14.1	51
	Present	128	77.1	79	85.9	207
	Total	166	100.0	92	100.0	258
Metaconule on the upper first molar	Absent	71	42.8	29	31.5	100
	Present	95	57.2	63	68.5	158
	Total	166	100.0	92	100.0	258
Hypocone on the upper second molar	Absent or cuspule	40	24.1	37	40.2	77
	Present	126	75.9	55	59.8	181
	Total	166	100.0	92	100.0	258
Distal accessory ridge on the lower canine	Absent	105	63.3	68	73.9	173
	Present	61	36.7	24	26.1	85
	Total	166	100.0	92	100.0	258
Lingual cusp number on the lower second premolar	One	45	27.1	25	27.2	70
	More than one	121	72.9	67	72.8	188
	Total	166	100.0	92	100.0	258

Table 9.4 (continued)

Dental traits		Ethnicity				
		Mongoloid	%	Indian	%	Total
Protostylid on the lower first molar	Absent	81	48.8	65	70.7	146
	Present	85	51.2	27	29.3	112
	Total	166	100.0	92	100.0	258
Deflecting wrinkle on the lower first molar	Absent	137	82.5	80	87.0	217
	Present	29	17.5	12	13.0	41
	Total	166	100.0	92	100.0	258
Metaconulid on the lower first molar	Absent	155	93.4	82	89.1	237
	Present	11	6.6	10	10.9	21
	Total	166	100.0	92	100.0	258
Entoconulid on the lower first molar	Absent	128	77.1	70	76.1	198
	Present	38	22.9	22	23.9	60
	Total	166	100.0	92	100.0	258
Cusp number on the lower second molar	Four	71	42.8	71	77.2	142
	More than four	95	57.2	21	22.8	116
	Total	166	100.0	92	100.0	258
Groove pattern on the lower second molar	+ and X	155	93.4	61	66.3	216
	Y	11	6.6	31	33.7	42
	Total	166	100.0	92	100.0	258

Table 9.5 Descriptive statistics of tooth size measurements in Mongoloids and Indians

Tooth	Sex	Ethnic: Mongoloid N	Mongoloid Mean	Mongoloid SD	Indian N	Indian Mean	Indian SD	Total N
Mesiodistal								
UI1	Females	88	8.47	0.54	42	8.42	0.44	130
	Males	78	8.74	0.46	50	8.71	0.32	128
	Total	166	8.60	0.52	92	8.58	0.41	258
UI2	Females	88	7.01	0.58	42	6.73	0.44	130
	Males	78	7.16	0.59	50	6.95	0.45	128
	Total	166	7.08	0.59	92	6.85	0.46	258
UC	Females	88	7.91	0.47	42	7.64	0.40	130
	Males	78	8.26	0.43	50	7.89	0.37	128
	Total	166	8.08	0.48	92	7.77	0.40	258
UP1	Females	88	7.36	0.44	42	7.17	0.36	130
	Males	78	7.54	0.42	50	7.31	0.41	128
	Total	166	7.44	0.44	92	7.24	0.39	258
UP2	Females	88	6.93	0.42	42	6.81	0.30	130
	Males	78	7.06	0.43	50	6.93	0.39	128
	Total	166	6.99	0.43	92	6.87	0.35	258
UM1	Females	88	10.40	0.53	42	10.43	0.44	130
	Males	78	10.66	0.52	50	10.60	0.53	128
	Total	166	10.52	0.54	92	10.52	0.50	258
UM2	Females	88	9.86	0.58	42	10.04	0.49	130
	Males	78	10.15	0.43	50	10.36	0.52	128
	Total	166	10.00	0.53	92	10.21	0.53	258

Tooth	Sex	Ethnic: Mongoloid N	Mongoloid Mean	Mongoloid SD	Indian N	Indian Mean	Indian SD	Total N
Buccolingual								
UI1	Females	88	7.13	0.45	42	7.00	0.51	130
	Males	78	7.38	0.48	50	7.38	0.41	128
	Total	166	7.25	0.48	92	7.21	0.49	258
UI2	Females	88	6.54	0.45	42	6.37	0.50	130
	Males	78	6.73	0.46	50	6.62	0.42	128
	Total	166	6.63	0.47	92	6.50	0.47	258
UC	Females	88	8.02	0.47	42	7.75	0.45	130
	Males	78	8.25	0.50	50	8.16	0.54	128
	Total	166	8.13	0.50	92	7.98	0.54	258
UP1	Females	88	9.48	0.43	42	9.31	0.43	130
	Males	78	9.79	0.58	50	9.75	0.46	128
	Total	166	9.63	0.52	92	9.55	0.50	258
UP2	Females	88	9.30	0.49	42	9.12	0.51	130
	Males	78	9.55	0.63	50	9.67	0.49	128
	Total	166	9.42	0.58	92	9.42	0.57	258
UM1	Females	88	11.11	0.48	42	11.08	0.54	130
	Males	78	11.57	0.54	50	11.56	0.48	128
	Total	166	11.33	0.56	92	11.34	0.56	258
UM2	Females	88	11.02	0.61	42	10.86	0.56	130
	Males	78	11.37	0.70	50	11.29	0.54	128
	Total	166	11.18	0.68	92	11.09	0.59	258

Table 9.5 (continued)

Tooth	SEX	Ethnic: Mongoloid N	Mongoloid Mean	Mongoloid SD	Indian N	Indian Mean	Indian SD	Total N
Mesiodistal								
LI1	Females	88	5.41	0.32	42	5.31	0.30	130
	Males	78	5.57	0.34	50	5.47	0.28	128
	Total	166	5.48	0.34	92	5.40	0.30	258
LI2	Females	88	5.97	0.34	42	5.81	0.37	130
	Males	78	6.14	0.34	50	5.95	0.34	128
	Total	166	6.05	0.35	92	5.89	0.36	258
LC	Females	88	6.79	0.40	42	6.58	0.32	130
	Males	78	7.22	0.39	50	6.90	0.38	128
	Total	166	6.99	0.45	92	6.75	0.39	258
LP1	Females	88	7.20	0.40	42	7.21	0.43	130
	Males	78	7.47	0.41	50	7.32	0.33	128
	Total	166	7.33	0.42	92	7.27	0.38	258
LP2	Females	88	7.21	0.45	42	7.19	0.37	130
	Males	78	7.42	0.47	50	7.38	0.39	128
	Total	166	7.31	0.47	92	7.29	0.39	258
LM1	Females	88	11.21	0.50	42	11.06	0.51	130
	Males	78	11.66	0.48	50	11.34	0.58	128
	Total	166	11.42	0.54	92	11.21	0.56	258
LM2	Females	88	10.19	0.50	42	10.34	0.39	130
	Males	78	10.64	0.58	50	10.61	0.36	128
	Total	166	10.40	0.58	92	10.49	0.40	258

Tooth	SEX	Ethnic: Mongoloid N	Mongoloid Mean	Mongoloid SD	Indian N	Indian Mean	Indian SD	Total N
Buccolingual								
LI1	Females	88	5.74	0.36	42	5.83	0.37	130
	Males	78	5.97	0.33	50	6.04	0.30	128
	Total	166	5.85	0.37	92	5.94	0.35	258
LI2	Females	88	6.18	0.35	42	6.17	0.32	130
	Males	78	6.30	0.42	50	6.34	0.37	128
	Total	166	6.24	0.38	92	6.26	0.36	258
LC	Females	88	7.22	0.48	42	7.08	0.46	130
	Males	78	7.42	0.57	50	7.20	0.46	128
	Total	166	7.31	0.53	92	7.15	0.46	258
LP1	Females	88	7.99	0.40	42	7.99	0.45	130
	Males	78	8.36	0.53	50	8.29	0.43	128
	Total	166	8.16	0.50	92	8.15	0.46	258
LP2	Females	88	8.52	0.41	42	8.59	0.50	130
	Males	78	8.81	0.42	50	8.98	0.42	128
	Total	166	8.66	0.44	92	8.80	0.50	258
LM1	Females	88	10.74	0.46	42	10.64	0.44	130
	Males	78	11.03	0.44	50	10.97	0.43	128
	Total	166	10.87	0.47	92	10.82	0.47	258
LM2	Females	88	10.43	0.45	42	10.38	0.48	130
	Males	78	10.80	0.56	50	10.75	0.46	128
	Total	166	10.61	0.54	92	10.58	0.50	258

Table 9.6 Hit ratios using all variables as input

			Predicted					
			Original			Tests sample		
	Observed		Mongoloid	Indian	%	Mongoloid	Indian	%
Step 1	Ethnicity	Mongoloid	152	14	91.6	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				88.8			86.3
Step 2	Ethnicity	Mongoloid	152	14	91.6	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				88.8			86.3
Step 3	Ethnicity	Mongoloid	152	14	91.6	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				88.8			86.3
Step 4	Ethnicity	Mongoloid	153	13	92.2	47	2	95.9
		Indian	16	76	82.6	8	16	66.7
	Overall Percentage				88.8			86.3
Step 5	Ethnicity	Mongoloid	152	14	91.6	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				88.8			86.3
Step 6	Ethnicity	Mongoloid	153	13	92.2	47	2	95.9
		Indian	14	78	84.8	8	16	66.7
	Overall Percentage				89.5			86.3
Step 7	Ethnicity	Mongoloid	155	11	93.4	46	3	93.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				89.9			84.9
Step 8	Ethnicity	Mongoloid	154	12	92.8	46	3	93.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				89.5			84.9
Step 9	Ethnicity	Mongoloid	155	11	93.4	46	3	93.9
		Indian	17	75	81.5	8	16	66.7
	Overall Percentage				89.1			84.9
Step 10	Ethnicity	Mongoloid	155	11	93.4	46	3	93.9
		Indian	16	76	82.6	8	16	66.7
	Overall Percentage				89.5			84.9
Step 11	Ethnicity	Mongoloid	155	11	93.4	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				89.9			86.3

Table 9.6 Continued

			Predicted					
			Original			Tests sample		
	Observed	Ethnicity	Mongoloid	Indian	%	Mongoloid	Indian	%
Step 12	Ethnicity	Mongoloid	156	10	94.0	48	1	98.0
		Indian	14	78	84.8	8	16	66.7
	Overall Percentage				90.7			87.7
Step 13	Ethnicity	Mongoloid	157	9	94.6	48	1	98.0
		Indian	13	79	85.9	8	16	66.7
	Overall Percentage				91.5			87.7
Step 14	Ethnicity	Mongoloid	156	10	94.0	47	2	95.9
		Indian	13	79	85.9	8	16	66.7
	Overall Percentage				91.1			86.3
Step 15	Ethnicity	Mongoloid	154	12	92.8	47	2	95.9
		Indian	16	76	82.6	8	16	66.7
	Overall Percentage				89.1			86.3
Step 16	Ethnicity	Mongoloid	154	12	92.8	47	2	95.9
		Indian	14	78	84.8	8	16	66.7
	Overall Percentage				89.9			86.3
Step 17	Ethnicity	Mongoloid	154	12	92.8	47	2	95.9
		Indian	13	79	85.9	8	16	66.7
	Overall Percentage				90.3			86.3
Step 18	Ethnicity	Mongoloid	155	11	93.4	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				89.9			86.3
Step 19	Ethnicity	Mongoloid	154	12	92.8	47	2	95.9
		Indian	14	78	84.8	8	16	66.7
	Overall Percentage				89.9			86.3
Step 20	Ethnicity	Mongoloid	155	11	93.4	47	2	95.9
		Indian	13	79	85.9	8	16	66.7
	Overall Percentage				90.7			86.3
Step 21	Ethnicity	Mongoloid	155	11	93.4	46	3	93.9
		Indian	15	77	83.7	9	15	62.5
	Overall Percentage				89.9			83.6

Table 9.6 (continued)

			Predicted					
			Original			Tests sample		
	Observed	Ethnicity	Mongoloid	Indian	%	Mongoloid	Indian	%
Step 23	Ethnicity	Mongoloid	156	10	94.0	46	3	93.9
		Indian	18	74	80.4	8	16	66.7
	Overall Percentage				89.1			84.9
Step 24	Ethnicity	Mongoloid	154	12	92.8	46	3	93.9
		Indian	19	73	79.3	8	16	66.7
	Overall Percentage				88.0			84.9
Step 25	Ethnicity	Mongoloid	153	13	92.2	46	3	93.9
		Indian	19	73	79.3	8	16	66.7
	Overall Percentage				87.6			84.9
Step 26	Ethnicity	Mongoloid	153	13	92.2	45	4	91.8
		Indian	18	74	80.4	8	16	66.7
	Overall Percentage				88.0			83.6

All combinations of linear regression models up to 26 steps give predictions that are statistically better than chance. Proportion chance criterion benchmark at 54% and 56% for original and tests sample respectively. All combinations of linear regression model also exceeded Press's Q critical value of 3.84 (1 degree of freedom; $p<0.05$)

Table 9.7 Hit ratios using 20 metric and 13 non-metric variables as input

			Predicted					
			Original			Tests sample		
			Ethnicity			Ethnicity		
	Observed		Mongoloid	Indian	%	Mongoloid	Indian	%
Step 1	Ethnicity	Mongoloid	152	14	91.6	46	3	93.9
		Indian	14	78	84.8	11	13	54.2
	Overall Percentage				89.1			80.8
Step 2	Ethnicity	Mongoloid	152	14	91.6	46	3	93.9
		Indian	14	78	84.8	10	14	58.3
	Overall Percentage				89.1			82.2
Step 3	Ethnicity	Mongoloid	152	14	91.6	45	4	91.8
		Indian	14	78	84.8	10	14	58.3
	Overall Percentage				89.1			80.8
Step 4	Ethnicity	Mongoloid	150	16	90.4	45	4	91.8
		Indian	14	78	84.8	11	13	54.2
	Overall Percentage				88.4			79.5
Step 5	Ethnicity	Mongoloid	153	13	92.2	45	4	91.8
		Indian	14	78	84.8	11	13	54.2
	Overall Percentage				89.5			79.5
Step 6	Ethnicity	Mongoloid	151	15	91.0	45	4	91.8
		Indian	14	78	84.8	10	14	58.3
	Overall Percentage				88.8			80.8
Step 7	Ethnicity	Mongoloid	151	15	91.0	46	3	93.9
		Indian	14	78	84.8	10	14	58.3
	Overall Percentage				88.8			82.2
Step 8	Ethnicity	Mongoloid	152	14	91.6	46	3	93.9
		Indian	11	81	88.0	10	14	58.3
	Overall Percentage				90.3			82.2

Table 9.7 (continued)

			Predicted					
			Original			Tests sample		
			Ethnicity			Ethnicity		
	Observed		Mongoloid	Indian	%	Mongoloid	Indian	%
Step 9	Ethnicity	Mongoloid	151	15	91.0	46	3	93.9
		Indian	13	79	85.9	10	14	58.3
	Overall Percentage				89.1			82.2
Step 10	Ethniciy	Mongoloid	151	15	91.0	46	3	93.9
		Indian	12	80	87.0	9	15	62.5
	Overall Percentage				89.5			83.6
Step 11	Ethnicity	Mongoloid	153	13	92.2	46	3	93.9
		Indian	14	78	84.8	9	15	62.5
	Overall Percentage				89.5			83.6
Step 12	Ethnicity	Mongoloid	154	12	92.8	46	3	93.9
		Indian	15	77	83.7	9	15	62.5
	Overall Percentage				89.5			83.6
Step 13	Ethnicity	Mongoloid	153	13	92.2	47	2	95.9
		Indian	15	77	83.7	9	15	62.5
	Overall Percentage				89.1			84.9
Step 14	Ethnicity	Mongoloid	152	14	91.6	47	2	95.9
		Indian	16	76	82.6	9	15	62.5
	Overall Percentage				88.4			84.9
Step 15	Ethnicity	Mongoloid	151	15	91.0	47	2	95.9
		Indian	18	74	80.4	11	13	54.2
	Overall Percentage				87.2			82.2

All combinations of linear regression models up to 15 steps give predictions that are statistically better than chance. Proportion chance criterion benchmark at 54% and 56% for original and tests sample respectively. All combinations of linear regression model also exceeded Press's Q critical value of 3.84 (1 degree of freedom; $p<0.05$)

9.4 Discussion

Random sampling had minor effects on the composition of the samples reported in this Chapter but the general pattern of morphological characteristics and tooth size differences between the samples in this Chapter and the original sample was consistent. This study can, therefore, be assumed to be representative of the original sample.

In previous discrimination studies, non-metric and metric data were analysed separately using discriminant function and binary logistic regression. The successful classification rates were quite similar, within the range of 67.6 to 76.7% for metric and 68.9 to 78.9% for non-metric data.

Combining metric and non-metric data in a binary logistic regression analysis improved the successful classification rate. Two approaches using this combination of data types, which took into account the practical difficulty of obtaining incisor measurements, especially of the labiolingual dimension, were employed. Firstly, all available data were entered into a stepwise analysis which generated 26 models with successful classification rates ranging from 87.6% to 91.5% for the original sample and 83.6% to 87.7% in the test sample. These outcomes were comparable with those of Matis and Zwemer (1971) and Lease and Sciulli (2005). Secondly, all data, except tooth size measurements for the incisors, were entered. This generated 15 models with successful classification rates of 87.2% to 90.3% in the original sample and 79.5% to 84.9% in the test sample. There seemed to be only minor loss of precision following the exclusion of incisor measurements from the analysis. It is reasonable to conclude that the package of prediction models developed would provide meaningful options for forensic odontologists to use in appropriate circumstances.

In real situations, the risk of missing postmortem evidence for analysis is always present. The requirement of more variables for analyses will restrict the use and application of these models. In addition, the presence of caries, restorations or tooth wear will limit the practicality of utilizing dental variation for human identification. The results from these studies provide three alternate models; metric data only, non-metric data only and a combination of both, for use in a variety of situations. For example, in cases of obvious interproximal wear which would hamper tooth size measurements, non-metric models could be used at the expense of a slightly lower successful classification rate. In an ideal situation, where all required variables were available, models using combined data types would be preferable because of the higher successful classification rates.

In conclusion, the performance of prediction models using odontometry and tooth morphology was as good as the use of craniometry to estimate between ethnic groups (Giles and Elliot, 1962). However, it is important to remember that the more variables that one included in the models the greater the likelihood that there will be missing values that will limit their practical application.

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Chapter 10 General discussion and conclusions

Studies of related individuals and recent discoveries in molecular biology have confirmed that there is a relatively strong genetic contribution to dental crown development in humans. Both sex (Garn *et al.*, 1967; Alvesalo and Tammisalo, 1981; Alvesalo *et al.*, 1987) and autosomal chromosomes (Townsend, 1978; Cobourne, 1999; Dempsey and Townsend, 2001) have been found to contribute to variation in tooth size and morphology. Tooth size in males tends to be larger, on average, than tooth size in females (Kieser, 1990) and there are patterns of tooth size variation and expression of dental crown traits that appear to be characteristic of certain ethnic groups (Scott and Turner, 1997). It is reasonable, therefore, to assume that variations in dental crown size and morphology in humans should be able to be used in a meaningful way to predict sex and ethnicity in anthropological studies and in forensic situations.

Previous reports by (Matis and Zwemer, 1971) and (Chiu and Donlon, 2000) have shown that discriminant function analysis can be applied successfully to tooth size data to enable groups to be separated according to ethnicity. Other researchers have indicated the forensic potential of tooth morphology for ethnicity classification (Tratman, 1950; Dahlberg, 1957; Lasker and Lee, 1957; Dahlberg, 1963; Scott and Turner, 1997) but relatively few predictive models have been developed specifically for use in forensic situations. A recent study, published by (Lease and Sciulli, 2005) involved application of logistic regression analysis to dental data. Success rates for determining ethnicity were high and comparable with previous results using discriminant function analysis but the study was confined to a sample of American children aged 2 to 6 years.

The globalisation of the world means that it is no longer acceptable to ignore international standards of identification when foreign nationals die in developing countries. This also means that nationals of these countries are coming to expect that similar principles will also apply to them. This expectation has been highlighted recently by a number of incidents where large numbers of people have lost their lives in terrorist and natural disasters, including 9/11, the Bali bombings in 2002 and 2005, the Asian Tsunami and the earthquake in Pakistan in 2005.

Dental identification has been shown to be an accurate, reliable and rapid method of scientific identification. Almost 60% of victims of the Tsunami in Thailand were identified by dental comparison (James, 2005). Traditional forensic dental identification is based on comparison of the restorative dental status of the deceased against comprehensive and

accurate ante-mortem dental records. Circumstances in many developing or poorer countries are such that caries levels may be low or access to extensive dental services may not be available to the majority of the population. The quality of the dental records kept by dentists may also not be high. In these situations, additional methods based on the most durable structures in the body, i.e. teeth, have considerable potential to assist in the identification process.

The value of dental data should not be underestimated even in circumstances where traditional identification techniques cannot be employed. Morphologic dental information could contribute to gender and ethnicity grouping of victims, enabling detailed examinations to apply to smaller, more manageable groups. Collaborative evidence could be provided in support of other scientific investigations, for example fingerprints, DNA, and physical evidence to enable confirmation of identification. An added benefit is that techniques based on the measurement or visual observation of dental crowns are not expensive or reliant on significant technology.

This project investigated variability of tooth size and dental crown morphology in Malaysian populations, with particular emphasis on application in forensic situations. Malaysia is a country where availability of dental services is high, but the level of dental record keeping is not adequate to guarantee identification can be achieved in every situation. Furthermore, no comprehensive descriptions of the nature and extent of dental variations in Malaysians currently exist.

Dental impressions of 790 individuals, representing the four main ethnic groups in Malaysia; Malays, Chinese, Indians and Jahai (Negritos), were obtained by the author over a 3-month period and stone dental models were constructed from these impressions. Tooth size and dental crown morphology were recorded from the dental models using digital callipers and visual observation. The data were analysed to determine within- and between-group variation using both univariate and multivariate analyses. Models to predict ethnicity and sex were developed and tested for accuracy.

Distance analysis using tooth size and morphological data suggested a close relationship between Malays and Chinese, with the Indians forming a separate group. The position of the Jahai fluctuated between these two divisions. Tooth size data placed them in a distinct and separate position, while morphologically they were closer to the Malays and Chinese. The small size of the Jahai sample did not permit use of multivariate analysis for predictive models but results from analyses of dental data for Malays, Chinese and Indians

showed that models could be developed that provided satisfactory predictive outcomes for determination of both sex and ethnicity.

The results for sex discrimination in this study were comparable with published findings in other populations (Garn *et al.*, 1977; Sciulli *et al.*, 1977; Brown and Townsend, 1979; Garn *et al.*, 1979; Haeussler *et al.*, 1989; Iscan and Kedici, 2003). Prediction rates ranged from 70 to 85%, indicating that the models would be useful in forensic situations. The applicability of using odontometry to predict sex was supported further in this study when it was found that probabilities of correctly predicting sex were not decreased when applied to cases where ethnicity was unknown.

Predictions of ethnicity were conducted successfully using two statistical approaches; discriminant function analysis and logistic regression analysis. The probability of correct classification was high and both approaches appeared to be potentially useful for forensic application. The most successful approach involved analysis of combined metric and non-metric dental variables using logistic regression. Ethnicity prediction was most successful when discriminating between Mongoloid (Malay and Chinese) and Indian groups. Accuracy of predictions was found to be over 87% for the test samples. As an example, step 13 (Appendix 9.1) selected 19 metric and 10 non-metric variables to provide the highest prediction rate.

This thesis has provided the first comprehensive description of variation in the dentitions of modern Malaysians, including the four main ethnic groups of Malays, Chinese, Indians and Jahai. By using a combination of univariate and multivariate statistical approaches, predictive models have been developed that enable the correct determination of sex and ethnicity with high levels of probability. The models include various combinations of tooth size measurements and dental crown features that could be applied in forensic situations where identification is important. The models have been developed from data derived from Malaysians and, in the first instance, are recommended for use within Malaysia. Similar studies in other countries would enable comparisons to be made and conclusions to be drawn about the generalizability of the methods used and the models developed. Further studies are also needed to determine the extent of genetic contributions to variation in the various dental crown features commonly used by dental anthropologists and forensic odontologists to determine sex and ethnicity. To date, only the genetic basis of Carabelli trait has been studied in detail, so there is plenty of scope for further research in this area.

My aim in completing this study has been to try to strengthen the scientific basis of forensic odontology in Malaysia, to increase awareness of the potential benefits of using dental

features in forensic situations, and to add to our general understanding of the origins and affinities of Malaysian people in a broader anthropological context.

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