ADAPTATION IN THE MASTICATORY SYSTEM

DESCRIPTIVE AND CORRELATIVE STUDIES OF A
PRE-CONTEMPORARY AUSTRALIAN POPULATION

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CONTENTS

PREFACE iv

STATEMENT v

ACKNOWLEDGEMENTS vi

SECTION 1: INTRODUCTION 1

1. Introduction 2

SECTION 2: MATERIAL AND METHODS 10

2. Material 11

3. Methods of Analysis 16
   - Univariate analysis 17
   - Bivariate analysis 17
   - Measurement errors 19
   - Bilateral symmetry 21

4. Sex Determination 22

5. Age Estimation 36
   - Study subjects 37
   - Methods 38
   - Results 40
   - Discussion 41

SECTION 3: DESCRIPTIVE STUDIES 44

6. Occlusal Attrition 45
   - Methods 53
   - Results 59
   - Discussion 62

7. Arch Dimensions 64
   - Methods 69
   - Results 71
   - Discussion 73

8. Occlusal Surface Direction 76
   - Methods 80
   - Results 82
   - Discussion 86
9. Craniofacial Morphology
   Methods  
   Results  
   Discussion  

10. Temporomandibular Joint Morphology  
    Methods  
    Results  
    Discussion  

11. Temporomandibular Joint Pathology  
    Methods  
    Results  
    Discussion  

SECTION 4: CORRELATIVE STUDIES  

12. The Dentition and Craniofacial Morphology  
    Methods  
    Results  
    Discussion  

13. The Dentition and the Temporomandibular Joint  
    Methods  
    Results  
    Discussion  

14. Craniofacial Morphology and the Temporomandibular Joint  
    Methods  
    Results  
    Discussion  

SECTION 5: SUMMARY  

15. Summary and General Discussion  

- 111 -
The teeth, the temporomandibular joints and the associated facial structures are subjected to continuing change throughout life as a consequence of normal growth processes, pathological conditions and adaptation to changes in masticatory function. The ability of the masticatory system to adapt to changing functional requirements by its intrinsic plasticity is an essential element in the maintenance of efficient relationships between the form and function of the system components.

A study of adaptive potential in the masticatory components has important implications for the understanding of biological processes in human skeletal tissues. In addition, it has significance in clinical dentistry where continuing efficient function in the masticatory system depends on the ability to adapt to changing functional conditions.

The aim of this study was to describe the teeth, joints and facial structures in a sample of Australian Aboriginal crania showing evidence of extensive tooth wear and degenerative change in the temporomandibular joints. Morphological relationships were also examined to provide an insight into the mechanism of adaptation to changing function.
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I declare that this thesis contains no material which has been accepted for the award of any other degree or diploma in any other university and that, to the best of my belief, it contains no material previously published or written by another person, except where due reference is made in the text.
Section One

INTRODUCTION
INTRODUCTION

The relationship between form and function in biological systems has intrigued morphologists from well before the concepts of natural selection and adaptability were consolidated by Darwin in the 19th century. Although variation has a genetic foundation which provides the mechanism of evolutionary progress, environmental factors have a profound effect upon morphology during the period of growth and, in many instances, well after adult form is attained.

The efficiency of a system is optimized by a close relationship between the morphology of the components and the functions they must perform. In addition to the biological adaptability which is largely genetic in origin and affects the species as a whole, the relationship between form and function also reflects the adaptive responses of individuals to the environment. Bonner (1961), in his discussion of D'Arcy Wentworth Thompson's well-known treatise "On Growth and Form", summarized these concepts in the following way:

"The fact that often the form is mechanically efficient is explained in two ways. If any given gene combination produces a structure of good mechanical design, it may, because of this, have a high adaptive value and remain in the population through favourable selection. In other instances there is clearly a direct effect of the environment which causes, by mechanical or physical forces, the form of a living structure. In the case of these direct adaptations we may assume that such responsiveness to the environment is adaptively advantageous and, therefore the gene complement that favours responsiveness or reactivity to the environmental conditions is favoured and maintained by selection."
This study is concerned with the general concept of adaptation to functional demands in the human masticatory system. Mastication is a primary activity which is executed most efficiently when the teeth, temporomandibular joints, musculature and supporting craniofacial structures share a close morphological and functional relationship. An understanding of the ways by which these relationships are maintained or modified by functional demands has relevance within the context of general evolutionary theory. Adaptation in the masticatory system is important in clinical dentistry also, in fields concerned with the treatment of conditions arising from stress on the dentition, joints and facial musculature.

The study of comparative anatomy provides many examples of the way in which components of the masticatory system have evolved under different conditions to suit functional demands. For example, it has been argued that the relatively inferior position of the temporomandibular joint, which is a common feature of carnivores, allows very wide mandibular opening and that the prominent canines and powerful masseter and temporalis muscles facilitate prehension of prey. In addition, the well-developed pre- and post-glenoid processes tend to enclose the mandibular condyle preventing mandibular dislocation by struggling prey. Well-developed mandibular elevator muscles combined with the sharp pointed cusps of premolar and molar teeth, provide an efficient mechanism for cutting and shearing food using predominantly vertical, chopping masticatory strokes. By comparison the flat occlusal surfaces, well developed lateral pterygoid muscles, specialized masseter muscles and the relatively superior position of the temporomandibular joints commonly seen in herbivores provide for broad masticatory strokes which facilitate the crushing and grinding of food (Noble, 1979).
In addition to these differences between species, there is clear evidence of evolutionary changes in the various components of the masticatory system within species. In hominids, the principal changes have been a decrease in the size of the teeth, facial skeleton and masticatory muscles and an increase in the size of the cranial vault (Weltz, 1979:154). The reduction in size of the masticatory components appears to parallel advances in the technology of food preparation and the consequent reduction in the functional demands placed on the teeth and their supporting tissue. Brace (1979), for example, provided evidence that there has been an average reduction of over 40 percent in the tooth crown areas of Europeans over the past 100,000 years. Similarly Hinton and Carlson (1979) found a progressive decrease in the dimensions of the temporomandibular joint with time. They described an average reduction of more than 7 percent in the total area of the temporal fossa over a period of about 2,000 years.

From a phylogenetic point of view the observed differences both within and between species probably reflect the gradual adaptation of the components of the masticatory system to environmental differences. In addition, growth mechanisms result in a degree of coordination between the components of the system. Both experimental (McNamara, 1980) and clinical investigations (Solow, 1980) of the relationship between dento-alveolar structures and the facial and functional patterns have been reported. Furthermore, the extent of this coordination has been quantified by correlation analysis of metric characters (Solow, 1966; Brown, 1969, 1973).
For efficient activity of the masticatory system it is important that coordination between functionally related structures is established during the growth and development of each individual and maintained throughout life. In recent times a number of investigators have discussed the adaptive ability of the masticatory system. Barrett (1969), for example, described the changes affecting teeth. He suggested that:

"The physical nature of the food determines the mode of mastication and the degree of tooth wear. The form of the teeth and their manner of occlusion are modified by tooth wear leading to gradual changes in the mode of mastication. And so ... on throughout life: functional adaptation to progressive but gradual changes in tooth form providing a functioning occlusion continually changing."

Barrett also described the situation when the functional demands exceeded the adaptive potential of the system and the dental tissues tended to "wear out" under harsh conditions. Continued loss of enamel and dentine from occlusal and incisal surfaces resulted in exposure of secondary dentine and subsequent exposure of the pulp chambers when tooth structure was lost at a greater rate than secondary dentine was deposited. Similarly, Blackwood (1966a,b) and others have suggested that degenerative changes in the temporomandibular joint arise in cases where the rate of joint surface remodelling required to accommodate the changing functional loads on the joint exceeds the adaptive potential of the joint surfaces involved.

Dental clinicians are becoming more aware of the importance of the relationship between the various components of the masticatory system in normal function. Posselt (1968), in his discussion of the physiology of
occlusion, suggested that:

"Normal or optimal function of the masticatory system is characterized by harmonious interactions between its various components."

Similar views were expressed by Ramfjord and Ash (1971:1) in the introduction to their textbook on dental occlusion. They described the masticatory system as:

"... a functional unit composed of the teeth, their supporting structures, the jaws, the temporomandibular joints, the muscles which are attached to the mandible, lip and tongue muscles, and the vascular and nervous systems for these tissues. A harmonious correlation between the component parts is of utmost importance for the functional capacity and maintenance of health within the masticatory system."

Despite a general awareness of the functional requirements for optimal mastication, relatively little is known of the precise nature of relationships between the various components of the system. This is probably a reflection of the theoretical and practical difficulties involved in their investigation rather than a lack of appreciation of the problem.

Major practical problems arise in devising suitable methods to select, quantify and analyse many of the variables involved. While some variables are easily quantified, others, such as temporomandibular joint morphology and craniofacial shape, are more difficult to describe and to date they have proved resistant to simple quantification (see Moyers and Bookstein, 1979a,b). The analysis of complex relationships between the
components of the masticatory system has been further complicated by the use of different measurement systems and rating scales, no doubt necessitated by the nature of the variables themselves. In addition, the multivariate nature of the problem complicates the analysis of pairs of variables which might be related either directly, or indirectly through common associations with other components of the system and common environmental factors to which each component has adapted. Unfortunately the currently available methods of multivariate analysis are not always appropriate and the interpretation of results can be difficult (Kowalski, 1972).

These problems, among others, explain the rather disappointing results obtained in many earlier studies. For example, Angel (1948) reasoned that the bony structure of the face should reflect the pattern of chewing because of its relationship to the direction of muscle action and that this should "shape" the temporomandibular joint. However, after a detailed study of the facial and temporomandibular joint morphology of a series of American Indian skulls, he could only conclude that:

"Individual differences in occlusion pattern fails to affect alveolar plane slope and has a much less certain effect than expected on eminence slope in spite of presumed difference in function with different occlusions."

More recently, evidence of direct associations between various components of the masticatory system has been reported. For example, Ingervall (1974) described the relationship between facial morphology and articular eminence slope and both Mongini (1972, 1975) and Seward (1976) provided evidence of an association between the pattern of tooth
wear and temporomandibular joint morphology. Similar studies have described the relationship between facial morphology and tooth wear (Murphy, 1959c; Fishman, 1976).

Preliminary evidence of this type suggests an association between the various components of the masticatory system. However, studies in which occlusal changes have been introduced in experimental animals have often failed to reveal any effects on the temporomandibular joint (Ramfjord and Hiniker, 1966; Ramfjord and Enlow, 1971). Story (1979), in a review of the controversies arising from studies of the temporomandibular joint, concluded that:

"... the anatomy of the temporomandibular joint, and by inference its movement, does not correlate with the occlusion."

There is, therefore, a clear need for further investigation of associations between components of the masticatory system. There are a number of ways in which such investigations might be approached. Each offers different advantages and disadvantages and no single method would appear to be ideal in every way. Studies of experimental animals, for example, do not necessarily provide relevant information because of the marked differences in craniofacial morphology and dental occlusion between species. Clinical studies are difficult either for ethical reasons or because, at present, the non-invasive methods for examination of the temporomandibular joints in particular, are not always reliable. Studies of skeletal material are limited by the absence of important soft tissue structures but offer considerable advantage in the ease of measurement of variables.
The study described here is based on a sample of crania obtained from a single, relatively isolated, precontemporary population of Australian Aboriginals. This material offered two important advantages: the high rate of tooth wear in the population provided evidence of continual, progressive modification to the dentition which could be related to changes in the other components of the masticatory system. In addition, by selecting a single isolated population, variation arising from inter-population differences was eliminated, allowing attention to be focussed on the short term adaptive changes rather than the variation due to evolutionary changes.

The report summarizes the findings of the investigation of this Aboriginal population and includes reference to the morphological features of the various components of the masticatory system and their inter-relationship in the presence of progressive occlusal changes.
Section Two

MATERIAL AND METHODS
Material for this study was selected from the collection of crania housed in the South Australian Museum. Each specimen was obtained from the region of South Australia formerly occupied by the Aboriginal people known as the Narrinyeri. All crania with 6 or more intact teeth were included in the study of the dentition. This provided a sample of 84 male and 72 female crania. From this group, 74 adult crania (37 male and 37 female) without damage to the temporomandibular joints and for which the required cranial reference points could be identified, were selected for detailed investigation in later parts of the study.

Many studies of both the physical and social anthropology of the Narrinyeri have been reported over the years since the first settlement of South Australia. Taplin (1874:1) began his account of the group in the following way:

"The people ... call themselves "Narrinyeri". The name is evidently an abbreviation of Kornarrinyeri (from kornar, man and inyeri, to belong to), and means "belonging to men". They take great pride in this designation, and call other nations of Aborigines wild blackfellows, while they say we are men. These Narrinyeri occupy a tract of country which would be included within lines drawn from Cape Jervis to a point about thirty miles above the place where the River Murray discharges itself into Lake Alexandrina and from thence to Lacepede Bay"

The exact tribal division of these people is not clear. Taplin's original description divided the group into eighteen tribes united as a "sort of confederacy". Tindale (1974:25), however, divided the same group into only five tribes (Jaraldekald, Portulun, Ramindjirl,
Tanganekald and Warki) and into fifty constituent clans, many of which correspond in name to tribes described by Taplin. Even though the Narrinyeri probably did not form a single tribe they are often considered as a single population in anthropological studies (eg. Capell, 1956; Howells, 1973:21).

The geographic isolation, cultural homogeneity and unique social and ritual behaviour of these people provide evidence of their status as a population. The Narrinyeri occupied the shores of a clearly defined river basin and associated lake system surrounded to the north-west by mountains, to the north-east by a dry and inhospitable hinterland and to the south by the sea (Figure 1). Even greater than any geographical barriers, however, were the cultural and ritual differences between these people and their neighbours. The eastern scarp of the Mount Lofty Ranges was the eastern limit of the rite of circumcision and as a result neighbouring tribes to the west (Kaurna and Permanck) did not regard the Narrinyeri as "real men" while the Narrinyeri regarded their circumcised neighbours as evil spirits (Tindale, 1974:134). Taplin (1874:2) records that the Narrinyeri also had little regard for their eastern neighbours. He reported that:

"They bore a special emnity to the Merkani because these latter had a propensity for stealing fat people and eating them. If a man had a fat wife, he was always particularly careful not to leave her unprotected lest she might be seized by prowling cannibals".

Despite considerable linguistic differences between the Narrinyeri and nearby groups (Meyer, 1846; Parkhouse, 1936), Tindale (1974:73) found evidence of occasional contact and exchange. Usually this occurred when the Narrinyeri needed to borrow fire from the Kaurna, obtain timber
for canoes from the hills or when, in cases of drought, eastern groups were admitted to the river at selected areas to obtain water. Tindale's Aboriginal informants could recall only one occasion when exchanges such as these had resulted in a marriage; a Tandanekald man married a woman from the most southern horde of the Kaurna and lived with her near the border between the two groups.

The physical and cultural barriers surrounding the Narrinyeri partly explain the cultural homogeneity of these people. In addition to Taplin's early observations, more recent investigations have described marked similarities between the constituent tribes of the Narrinyeri federation. For example, Brown (1918) found no significant social or linguistic differences between the tribes of the area, and Harvey (1943), in his discussion of the fishing legend of the Jaraldeckald, pointed out that it was shared with neighbouring Narrinyeri groups.

While the cultural homogeneity of the people from this area has been documented by early investigators after discussions with surviving members of the tribe, the temporal homogeneity of the skeletal material available is less easily confirmed as estimates of its exact antiquity are not possible. There is reason to believe, however, that most of the material represents individuals who were alive at the beginning of the nineteenth century. At about that time a smallpox-like epidemic spread down the River Murray resulting in the death of hundreds of Aboriginal people (Angus, 1847:86; Taplin, 1874:32; Stirling, 1911). There are a number of reasons to believe that most of the material included in the present study represents the remains of people who died at that time.
Firstly, the method of burial of most of the corpses differed from traditional Narrinyeri burials in several ways. Under normal circumstances the method of disposal of a corpse depended on the status of the individual in the society. Angus (1847:95) recorded that:

"When a young man dies, or a warrior is slain in battle, his corpse is set cross-legged upon a platform, with its face towards the rising sun; the arms are extended back, and all the apertures of the body are sewn up; the hair is plucked off, and the fat of the corpse, which had previously been taken out, is now mixed with red ochre, and rubbed all over the body. Fires are then kindled underneath the platform, and the friends and mourners take up their position around it, where they remain for about ten days, during the whole of which time the mourners are not allowed to speak; a native is placed on each side of the corpse, whose duty it is to keep off the flies with bunches of emu feathers, or small branches of trees ... After the body has remained for several weeks on the platform, it is taken down and buried."

This same ceremony has been described by Taplin (1874:17) and by Berndt (1940).

The remains of old men and children were not treated with the same ceremony but were still placed on elevated platforms and left to rot until "the structure falls to pieces". The remains were then gathered up and buried in the nearest patch of soft earth (Angus, 1847:94).

By comparison the corpses of the old women were regarded as unimportant. Angus (1847:94) described how:

"The bodies of aged women are dragged out by the legs, and either pushed into a hole in the earth, or placed in the forked branches of a tree; no attention whatever being paid to their remains."
Angus (1847:68) also described how, under normal circumstances, corpses were not buried with the "head on" and how:

"The natives around Lake Albert and the adjoining portions of the Coorong use the skulls of their friends as drinking vessels. After detaching the lower jaw, they fasten a handle of bull rush fibre to them, and carry them, whenever they travel, filled with water."

Much of the material studied here was obtained from large cemeteries, the best described of which was at Swanport on the River Murray. The fact that in many cases the skeletons were intact suggests that the people were buried at a time when the death rate was unusually high and normal burial rituals could not be performed (Stirling, 1911). In addition the calvaria of most subjects are intact implying that the remains had not been subjected to the normal ritual treatment before burial. Furthermore, radiographs and visual examination showed very little of the post-mortem mineralization commonly seen in more ancient material and many specimens retained a wax-like appearance in areas of dense bone as evidence of lipid remnants in the marrow spaces.

Based on this evidence anatomists and physical anthropologists have considered skeletal material from this area as a single population. For example Howells (1973:21), after discussion with Dr Tindale, considered the material to be "one of the nearly ideal samples" included in his investigation of skeletal populations, representing "a real local and time-limited sample".
CHAPTER 3

METHODS OF ANALYSIS

Various aspects concerned with the pattern of dental attrition, dental arch dimensions, slopes of occlusal surfaces, craniofacial morphology and temporomandibular joint morphology and pathology were assessed by the methods described in the appropriate sections. The data obtained were of several forms.

Many variables such as craniofacial and dental arch dimensions, occlusal surface directions, the extent of dental attrition and some aspects of temporomandibular joint morphology were measured on continuous scales. A number of variables were not so readily measurable, however. Degenerative change in the temporomandibular joint, for example, was clearly progressive in nature but could not be measured on a continuous scale. For variables such as these, subjects were ranked according to the extent or severity of the character considered and scores were assigned to defined stages. In a number of cases the variable to be assessed was qualitative rather than quantitative. In the case of condyle morphology, for example, 5 condyle shapes were identified and scores were assigned to each type. These scores simply enabled certain attributes of the condyles to be characterized and so increasing values did not imply any progressive change in condyle morphology.

The data obtained were subjected to several types of analysis depending on the nature of the scale on which the variable was assessed and the hypothesis being tested. In each case the simplest appropriate statistics were employed to describe and compare groups. Unless
otherwise stated the analysis was performed using the appropriate routine from the Statistical Package for the Social Sciences (S.P.S.S.) Version 8.0 (Nie et al., 1975) operating on a C.D.C. Cyber 173 system at The University of Adelaide. The formulae used in the routine statistical tests are included in Appendix 1.

Univariate analysis

The distributions of continuous variables were generally described by the mean (X), standard deviation (s) and the minimum and maximum values for the sample considered. The skewness and kurtosis values for variables of this type were also estimated as a guide to the form of the distribution, but in most instances the sample size was too small to assess probability levels.

The distributions of scores for variables which were not assessed on continuous scales were described in frequency tables.

Bivariate analysis

Several different forms of bivariate analysis were employed. The choice depended on the measurement scale on which the variables were assessed. In most cases the strengths of associations between pairs of continuous variables were quantified by Pearson's product-moment correlation coefficient (r). This is a standardized covariance coefficient which measures the variability which the pair of variables share in common.
In cases where the mean values and standard deviations for each variable of a pair were equal and where the order of the pairing was not important, Fisher (1958:211) suggested that the intra-class correlation coefficient \( r' \) should be used in preference to the product-moment correlation coefficient. In these cases a common mean \( (\bar{X}') \) and a common standard deviation \( (s') \) can be derived for the pooled sample:

\[
\bar{X}' = \frac{\Sigma (X_1 + X_2)}{2n}
\]

\[
s' = \sqrt{\frac{\Sigma (X_1 - \bar{X}')^2 + \Sigma (X_2 - \bar{X}')^2}{2n}}
\]

where "\( X_1 \)" and "\( X_2 \)" are paired variables.

The intra-class correlation coefficient is calculated as:

\[
r' = \frac{\Sigma (X_1 - \bar{X}')(X_2 - \bar{X}')} {n(s')^2}
\]

This should provide a more reliable estimate of the true correlation than the product-moment correlation coefficient because the estimates of the mean and standard deviation are based on "2n" values rather than "n" values.

In cases where changes in a dependent variable \( (Y) \) were assumed to be the result of, or were to be predicted from changes in an independent variable \( (X) \), linear regression equations of the form:

\[ Y = aX + b \]
were derived to describe the relationship. This method assumes that the independent variable is measured without error and is fixed for the purposes of the comparison. The relationship between age and attrition was described in this way (see Chapter 5). Age was the independent variable, the value of which was fixed in each case and attrition was the dependent variable the extent of which was related to the age of the subject considered.

In bivariate analyses where one of the variables to be compared was not scored on a continuous scale, one of a number of statistical tests was applied to determine the significance of the relationship between the pairs of variables considered. Either Student's t-test was used to compare the mean scores for the continuous variable between groups determined on the basis of scores on the other variable, or, by dividing the continuous distribution into subjects with high and low scores, the Chi-square test was used to assess the significance of deviations from expected distributions. Similarly the Chi-square test was used in cases where neither variable had been assessed on a continuous scale.

In addition to a number of analytical methods which had special application and are discussed later, 2 types of analysis were employed in several parts of the study. They involved the analysis of measurement errors and the assessment of symmetry.

Measurement errors

To assess the significance of measurement errors, 20 randomly selected subjects were examined on two occasions, 3 or more months apart and the differences between first and second determinations compared by the t-test for paired samples. This provided an indication of any
consistent differences between first and second measurements which might have arisen from inconsistencies in landmark identification or measurement technique or as a result of variation in the performance of measurement equipment. In addition the standard deviation of a single measure \( s_s \) was calculated according to the method of Dahlberg (1940:122) where:

\[
s_s = \sqrt{\frac{\sum (X_1 - X_2)^2}{2n}}
\]

and "\( X_1 \)" and "\( X_2 \)" are two repeated measurements and where "\( n \)" is the number of double determinations performed. The mean difference between first and second measurements, the standard error of the mean difference and the standard error of a single measure \( s_s \) were obtained using the program DOUBLE described in Appendix 2. The standard deviation of a single measure was used to determine the extent to which the variability due to experimental error affected the observed variance of the population. The observed variance \( s_o^2 \) can be considered to be the sum of the error variance \( s_e^2 \) and the true sample variance \( s_t^2 \):

\[
s_o^2 = s_t^2 + s_e^2
\]

The error variance was obtained from the standard deviation of a single measure:

\[
s_e^2 = s_s^2 = \frac{\sum (X_1 - X_2)^2}{2n}
\]

and was expressed as a percentage of the observed variance to provide an indication of the significance of the error variance.

- 20 -
The reliability of the non-metric scoring methods was also investigated. In this case all subjects were re-examined 3 or more months after the initial examination. The difference between first and second determinations was expressed as the percentage of discordant scores compared with the total number of re-examined subjects.

Bilateral symmetry

Symmetry in bilateral structures was assessed in a number of ways. For continuous, metric variables the t-test for paired samples was applied to determine whether any consistent differences between left and right sides were present. It was possible, however, that a small mean difference might arise where there was an approximately equal number of cases of relatively large differences of opposite sign between the sides. Therefore when the mean difference between sides did not differ significantly from zero, the intra-class correlation between scores for left and right sides was also calculated to provide an indication of the strength of the association.

In the case of variables assessed on non-metric scales, the distribution of scores for left and right sides was compared by examination of tables showing the frequency of concordant and discordant scores for left and right sides.

A number of other special methods were also employed in the analysis of the data. They will be described in the chapters in which they are used.
CHAPTER 4

SEX DETERMINATION

Because many adult dimensions display sexual dimorphism, the determination of sex is important in morphological studies. There are, however, a number of difficulties in determining the sex of skeletal material. For example the age-at-death of subjects may complicate assessment, and older females can be confused with younger males particularly if sex characteristics are not pronounced as is often the case in the latter group. In addition, because many of the criteria used to differentiate male and female material are reflections of general robusticity and consequently show significant inter-population differences, the preparation of universal standards is not possible. As a result the male and female limits for the characters being considered should be defined specifically for the population being considered.

When complete skeletons are available, the sex of subjects can usually be accurately determined. For example, after examining the skeleton, Krogman (1962:112) correctly determined the sex in each of 750 subjects. His assessments were less accurate, however, when only the pelvis (95 percent), skull (92 percent) or long bones (80 percent) were available. Other observers, while noting the same trends, have not had the same success; Stewart (1957) correctly sexed only 94 percent of complete skeletons and 77 percent of crania. Krogman recognised that his task was simplified by the strong predominance of males in his sample; by always assigning doubtful subjects to the male group he increased his chance of correct assessment considerably.
When only fragmented material is available it is generally agreed that the pelvis provides the most reliable indicator of sex, and both morphological and metric sex differences in pelvic morphology have been described (see Krogman, 1962:122-142 for a review). At a recent Workshop of European Anthropologists (1980) methods for sex determination from observations of the scapula, clavicle, sternum, vertebrae, talus and calcaneus were also described but these are generally regarded as being less reliable. Similarly, while the dimensions of long bones differ significantly between the sexes, the degree of overlap makes determinations based on these criteria of little use, especially if the population from which the material was obtained is not known.

When only the skull is available, as is frequently the case in anthropological studies, both morphological and metric methods can be used to determine the sex of the subject. The morphological differences between male and female skulls are well-defined (Krogman, 1962:114-122; Workshop of European Anthropologists, 1980). Males are characterised by:

1. Larger overall size,
2. Generally more rugged appearance,
3. Larger supra-orbital ridges,
4. Larger mastoid processes,
5. More marked external occipital protruberance,
6. Smaller frontal and parietal protruberances,
7. Small, lower, squarer orbit with more rounded margins,
8. Steeper, less rounded forehead,
9. Heavier, higher zygomatic process,
10. Larger, broader, more "U"-shaped palate,
11. Larger occipital condyles,
12. More prominent chin,
13. More strongly marked, everted gonial angle,
14. Higher mandibular symphysis, and
15. Broader ascending ramus of mandible.

It is generally accepted, however, that even under ideal conditions, about 10 percent of crania cannot be confidently assigned to either sex (Giles, 1970).

Discriminant function analysis provides a more objective method of sex determination based on combinations of metric variables. Linear functions relating variables known to show a high degree of sexual dimorphism can be generated which will give maximum discrimination between scores for males and females. From the distribution of these scores a section point and confidence limits can be generated. Scores can then be calculated for subjects of unknown sex and their probable sex determined. Despite its objective nature, sex determination by discriminant function is probably no more reliable than morphological sexing. The 21 functions based on cranial measurements, described by Giles and Elliot (1963), misclassified from 12.4 to 16.5 percent of their American sample. Functions derived for Finnish cranial by Kajanoja (1966) were even less reliable, misclassifying about 23 percent of subjects.

Irrespective of the method employed, the male and female limits of morphological characters need to be defined specifically for the population considered, and in general this has been difficult in studies of Australian skeletal material where skeletal populations of known sex are not available. In relatively recent times sex determination methods have been developed specifically for Australian Aborigines.
Many of the innominate bones of Narrinyerl subjects show reference points marked by Davivongs (1963a) who described the sexual dimorphism in pelvic morphology in specimens from the South Australian Museum collection. He found that the Ischium-pubic Index, the diameter of the acetabulum and measurements of the relative breadth and depth of the greater sciatic notch showed the largest differences between males and females. Sex could be accurately assigned in 91 to 97 percent of cases based on any one of these criteria.

Davivongs (1963b) also described sex differences in the Australian femur. Based on his data, femoral head dimensions should provide an accurate indication of sex in about 95 percent of cases, but the sex assigned on the basis of transverse condylar dimensions would be accurate for only 90 percent of subjects. Relatively smaller sex differences in the clavicle, humerus and scapula have also been described. Both Ray (1959) and van Dongen (1963) found that the morphology of the clavicle provided little information about the sex of the subject. Of the three bones considered by van Dongen the proximal articular surface of the humerus showed greatest sex difference, but the considerable overlap of male and female values limited the usefulness of these criteria for sex determination.

Despite the fact that Hrdlička (1928) found the sexing of the Australian skull was "not always easy", most early studies of Australian crania relied on morphological sexing (eg. Klaatsch, 1908; Fenner, 1939). Larnach and Freedman (1964) developed a sex determination method for Australian Aboriginal crania from the east coast of Australia. They assigned a score of 1 to the most female and a score of 3 to the most male form of the following characters:
1. Glabella prominence
2. Superciliary ridge prominence,
3. Development of the zygomatic trigone,
4. Prominence of the malar tuberosity,
5. Ruggedness of the occipital markings,
6. Mastoid process size
   (assessed as length X breadth X depth /100), and
7. Palate size
   (assessed as alveolar length X breadth /100)

The sum of the scores provided an indication of the sex of subjects; where the total of the scores was greater than 11 the subject was assigned to the male group. Using this method Larnach and Freedman correctly assigned sexes to 92.5 percent of their sample of 117 crania.

Brown (1981) described the application of the Larnach and Freedman method to a series of crania from the Murray Valley and found that it assigned most subjects to the male group unless the female limit was increased by two units, suggesting that in the same way as the section points of discriminant functions need to be specifically defined for racial groups, so they need to be adjusted between closely related populations.

Larnach and Macintosh (1971) described a method for sex determination based on mandibular morphology. They assigned scores in the same way as for the method based on observations of the skull, to the following mandibular features:
1. Maximum breadth of ramus: narrow < 38mm; wide > 42mm,
2. Minimum breadth of ramus: narrow < 30mm; wide > 33mm,
3. Height of ramus: low < 58mm; high > 63mm,
4. Bigonial breadth: narrow < 91mm; wide > 97mm,
5. Total mandibular length: short < 101mm; long > 107mm,
6. Symphysis height: low < 30mm; high > 33mm,
7. Area of planum triangulare,
8. Eversion of gonial angle,
9. Anterior marginal tubercle,
10. Depth of sigmoid notch: shallow < 10mm; deep > 13mm,
11. Sulcus interorallis.

The sum of the scores provided an indication of the sex of the subject. Subjects with scores of 19 or less were assigned to the female group. The sex assigned in this way agreed in every case with the sex assigned by the Larnach and Freedman method.

These investigations highlight the principal limitation of almost all of the methods developed for sex determination of Australian Aboriginal skeletal material. Of the 117 subjects on which the Larnach and Freedman method for sex determination from observations of the skull was developed, only one was of known sex; a further eighteen were sexed by examination of both the skull and available post-cranial skeleton but for the remaining 98 subjects (84 percent of the sample) sex was determined by examination of the skull alone. As Giles (1964) concluded, the:

"... sexing of skeletal material by discriminatory analysis of morphology when visual appreciation of the same morphology has been used for the original sex determinations can never be quite satisfactory."

- 27 -
The close correspondence between "actual" and assigned sex is, in a sense, an indication of the replicability of assessment of morphological characters rather than an indication of the power of the method in determining the sex of subjects. The methods described by Davilvongs (1963a,b) and van Dongen (1963) for the post-cranial skeleton suffer from a similar problem. In each of these studies, sex was assigned on the basis of the investigator's assessment of pelvic morphology since actual sex was not known.

Until recently only one method of sex determination based on Australian Aboriginal material of known sex had been reported. Brown and Townsend (1979) developed a discriminant function method for the assignment of sex from measurements of the mesiodistal and buccolingual dimensions of teeth. While the teeth are ideal in that they, unlike the skeletal components, can be measured directly in living subjects of known sex, the functions developed for tooth measurements did not provide very reliable assessments of sex. The best theoretical function, including the mesiodistal and buccolingual dimensions of all except the third molars, should in theory correctly assign sexes to 85 percent of subjects but, when applied to a test sample, the assigned and actual sex agreed in only 68 percent of subjects.

A suitable method of sex determination should be specific for the population considered and be derived from a sample of known sex. In addition, functions should be reliable, correctly assigning at least 85 percent of test subjects. At present none of the methods available for the determination of sex in studies of Australian Aboriginal material satisfy more than two of these criteria.
Apart from the lack of a reliable method for sex determination, the study of the Narrinyeri population presented a number of additional problems. Firstly post-cranial skeletal remains were available for only 7 of the 156 subjects examined in various parts of the study, preventing the application of the more reliable pelvic criteria. In addition, skull and mandible were available for only 89 subjects, the skull alone for a further 56 subjects and the mandible alone in 15 cases.

Because of these problems the following procedure was adopted. Firstly, a provisional assignment of sex was made for each of the skulls on the basis of the overall appearance of the subject, taking into account the criteria described by Larnach and Freedman (1964), and Larnach and MacIntosh (1971).

Measurements of selected craniofacial variables were obtained by the methods described in Appendix 5 and discriminant function scores were then calculated for each subject using function number 6 described by Giles and Elliot (1963) where:

discriminant score =

\[ 4.692 \times \text{glabello-occipital length} + 1.000 \times \text{maximum cranial breadth} + 8.769 \times \text{basion-bregma} + 4.615 \times \text{basion-nasion} + 21.305 \times \text{bzygomatic diameter} + -4.385 \times \text{basion-prosthion} + 7.385 \times \text{prosthion-nasion} \]
This was selected because it provided the most reliable results in the test sample of white and Negro subjects used by Giles and Elliot, correctly assigning sexes to 86 percent of subjects. In addition, application of the function to a group of Australian Aboriginal subjects of known sex using measurements obtained from radiographs, showed that, after redefining the section point, the function correctly classified 92 percent of a test population of 100 subjects (Townsend, Richards and Carroll, 1982).

To assign sexes to the Narrinyerl subjects, the mean scores for crania provisionally assigned to the male and female groups were calculated and the section point set midway between these means. Sex assigned in this way was then compared with the provisional sex and, in the case of any disagreement, subjects were reexamined and reassigned where necessary. The male and female means and the section point were then recalculated and the distributions plotted (Figure 2). Subjects in the region where the male and female scores overlapped (scores of 5960 to 6100) were examined by two other independent observers (Professor T. Brown, The University of Adelaide and Peter J. Brown, The Australian National University). Where their assessment disagreed the subjects were excluded; this occurred in only one case (Subject A660) where agreement could not be reached.

To determine the sex of a subject from the appearance of the mandible alone is quite difficult, therefore discriminant function scores using function number 6 described by Giles (1964) for the mandible were calculated for each subject using the formula:
Discriminant score =

1.510 X mandibular symphyssis height +

-1.895 X mandibular body height +

1.035 X mandibular body length +

2.568 X mandibular ramus height +

1.000 X bigonial breadth

This function was chosen because, of the functions developed for combined Negro and white American samples, it showed the smallest theoretical probability of misclassification (14.7 percent).

Mandibles were available for 114 subjects. Of these, sex had been assigned on the basis of cranial morphology in 99 cases. Discriminant function scores for the mandibles of these subjects were considered and the male and female means and section point calculated (Figure 3). This section point was then used to assign sexes to the 15 remaining isolated mandibles.

Previous investigators have published data (including sex determinations) for much of the material considered in this study. Sexes assigned by the method described here were compared with those reported by Hrdlička (1928) and Brown (1973). Of the 24 subjects included in Hrdlička's "Catalogue of Human Crania" and also studied here, sexes agreed in only 14 cases (58 percent). Five of the the fourteen males listed by Hrdlička were classified as female in this study and half of Hrdlička's females were assigned to the male group. Of these, three (A42, A50 and A98) were described by Hrdlička as being from either Adelaide or Glenelg, but Museum records clearly show that they were excavated at the Swanport site suggesting that there might have been some confusion over the identification of a number of specimens. The 2

- 31 -
remaining subjects (A91 and A306), both show clearly male discriminant function scores (6186 and 6250 respectively) and one (A91) is clearly male in appearance (Figure 4a,b).

Brown's (1973) study of the cranial morphology of the Australian male included 30 of the same Narrinyeri subjects considered in this study. In only one case did his sex assignment differ from that in this study. Subject A16521 was assigned to the female group in this study on the basis of its relatively gracile mandible and small discriminant function score (5879) but is possibly male if the extensive brow ridging is considered (Figure 4c).

In the 7 cases where innominate bones were available, the criteria described by Davivongs (1963a) were used to obtain an indication of the sex of the subject. In one case (A61) the skull appeared clearly male but the pelvis showed strong female characteristics. The same conflict was noted by Howells (1973), who concluded that the skull and pelvis were from different subjects. In the remaining cases the sex assigned on the basis of pelvic criteria agreed with that assigned by the method described here.

Discriminant function scores and the final sex assignment for all subjects considered are included in Appendix 3.
A main objective of the present study was to examine morphological changes in the craniofacial skeleton, dentition and temporomandibular joints. Changes may be age-related, initiated by functional determinants, or, in many instances, they may be related to a combination of several factors. The estimation of age-at-death of the material examined was therefore an important consideration in this investigation. However, this can be complicated by population differences in the rate and extent of the aging process and by environmental factors such as nutrition and disease which affect individuals in different ways.

When the complete skeleton is available, age estimates can be obtained from the observed pattern of changes in synarthrodial joints. For males aged less than 40 years, changes in the pubic symphysis are closely related to age (Todd, 1920; Todd and Lyon, 1924, 1925; McKern and Stewart, 1957; Hanihara and Suzuki, 1978). Krogman (1962:111) suggested that these changes can provide age estimates accurate to within five years but in females the trauma of parturition can result in scarring which limits the value of the method (Gilbert and McKern, 1973). Furthermore, the last described stage is usually reached by age 40 years so that use of the method is limited to relatively young subjects (McKern and Stewart, 1957). More recently, methods for estimating age from changes in the chondro-costal joints and vertebral bodies have been described, but neither provide very precise estimates (Kerley, 1970). In the case of the vertebral bodies, the possibility of superimposed arthritic change complicates assessment.
Morphological changes in bone can also provide an indication of a subject's age at death. Acsádi and Noméskéri (1970) described age-related changes in the trabecular pattern in the heads of the femur and the humerus and Kerley (1965, 1969, 1970) described age-dependent changes in the histological appearance of cortical bone. In addition, Lengyel (1968) found that within populations the carbonate, phosphorous and collagen levels of bone vary consistently with age.

A number of age estimation methods are based on cranial features alone. Todd and Lyon (1924, 1925) described the progressive fusion of cranial sutures with age. It is generally agreed, however, that estimates obtained in this way are not always reliable (Brooks, 1955; Krogman, 1962:89). Todd and Lyon also found evidence of thinning of the parietal bone in subjects older than 60 years but because there is considerable variation in this process it has little value other than to corroborate estimates obtained by other methods.

Of the methods for aging that rely on changes in the teeth, Gustafson’s (1950) is considered by many to provide the most accurate estimates (Kerley, 1970). Modifications of this method have been proposed by Dalitz (1962), Miles (1963), Bang and Ramm (1970) and Johanson (1971) but, essentially, each relies on the pattern of age-related changes in the tooth crown and root. Solheim and Sundnes (1980) compared the reliability of these methods and concluded that while estimated age was within 10 years of actual age in more than 85 percent of cases, age tended to be underestimated for young subjects, for males, and for the maxillary teeth.
Because dental attrition is progressive, age estimates can also be obtained from observations of the dental wear pattern. In earlier studies, when simple ordinal scales were used to assess attrition, subjects were often assigned to age groups with broad limits according to attrition scores. For example, Abble (1950) assigned subjects to age groups encompassing successive ten year intervals based on attrition scores, using the age-attrition tables developed for Australian Aborigines by Campbell (1939).

By assuming that the intervals between molar eruption times showed little variation and that attrition progressed at a constant rate, Miles (1962) was able to estimate age from the pattern of wear on the mandibular molars. After establishing the rate of wear in immature subjects, for whom relatively accurate age estimates were obtained from the patterns of tooth emergence, ages were estimated for older subjects by a process of extrapolation. When estimates obtained from adjacent teeth by this method were compared they generally displayed very small differences (Helm and Prydsø, 1979). Similarly, estimates based on upper and lower arches were usually highly correlated. For example, Nowell (1978) found that scores obtained from maxillary and mandibular molars agreed within five years in 93 percent of cases. However, the method is yet to be tested on a population of known age and so its reliability is unclear.

Sagne (1976) used a similar method to develop a linear regression model relating ages obtained from tooth eruption times in young subjects to attrition scores for molar teeth considered separately. Ages were then estimated for older subjects by extrapolation. The method, however, appeared to underestimate the age of older subjects suggesting that the
relationship between age and attrition may not have been linear over the entire age range.

Recently Tomenchuk and Mayhall (1979) described a close relationship between maxillary molar wear and recorded age in a group of Eskimo subjects. Their TOOTH WEAR INDEX (TWI) calculated as:

$$\text{TWI} = \frac{100 \times \text{cusp height}}{\text{mesio-distal} \times \text{bucco-lingual dimension}}$$

provided an objective, quantitative measure of attrition, and regression equations relating age and attrition scores led to relatively accurate age estimates. However, the method can be applied only when cusp morphology is not obliterated by wear. In addition, Tomenchuck and Mayhall were not convinced that the age-attrition relationship was necessarily linear over the range they considered.

Because only skulls were available for the majority of the Narrinyeri population included in this study, age estimation methods which rely on observation of the post-cranial skeleton could not be applied. In addition, histological and chemical methods, which require destruction of tissue, were not appropriate because of the uniqueness of the material. Although tables of cranial suture fusion times in Australian Aboriginals have been developed by Abble (1950), his age categories have broad limits. This method was not entirely suitable for the purposes of the present study where more precise estimates were required.

Unfortunately insufficient immature Narrinyeri subjects were available to determine attrition rates from ages based on standards of tooth eruption. The method was investigated but, because of the poor
reliability of the estimated attrition rates derived from the few available young subjects, differences between ages estimated from maxillary and mandibular teeth were consistently large in the older subjects. Consequently alternative methods of age estimation were investigated.

Study Subjects

To investigate the relationship between age and attrition, dental casts of Australian Aboriginals with either known ages or reasonably reliable age estimates, from three locations were examined (Figure 5). The first group were members of the Kuini, Kalari, Walambi and Warmala tribes living at Kalumburu, a Benedictine Mission situated at the mouth of the King Edward River in the north-west of Australia (Perez, 1958). Casts of these subjects were obtained by Brown (1964) who reported on the distribution of oral pigmentation.

The second group were desert dwelling members of the Aranda tribe living at Haasts Bluff in the Northern Territory, 260 kilometres west of Alice Springs. Casts of this group were obtained by Heithersay (1959, 1960, 1961). A third small test sample was selected from casts obtained from Walbiri subjects registered in a longitudinal growth study at Yuendumu, a government settlement about 290 kilometers north-west of Alice Springs (Barrett, 1976). Attrition scores for ten teeth from this group were used to test the accuracy of the age prediction equations developed from the other two populations. Ages of the subjects at the time the casts were obtained were noted from official records and verified after physical examination. The age and sex distribution of the subjects from Kalumburu and Haasts Bluff are shown in Table 1.
Methods

Dental casts were photographed with the occlusal plane defined by the central fossae of the second molars and the incisal edges of the central incisors parallel to the focal plane of the camera. Before photography, the casts were secured in a surveying table and the occlusal plane orientated using a specially constructed tripod fitted with a bubble level indicator (Figure 6). Oblique lighting facilitated identification of exposed dentine. Transparencies of the dental casts were orthogonally projected onto a viewing screen to provide an enlargement of approximately 15 times and the images traced onto paper (Figure 7). Attrition scores were obtained for all first and second molars in the manner described in Chapter 6.

To determine the presence of asymmetry in tooth wear, the scores for the Kalumburu and Haasts Bluff subjects were combined and the differences between right and left sides were assessed by the t-test for paired samples (Table 2). The observed differences were significant only for the maxillary first and second molars. Although some degree of asymmetry in attrition was detected, with the right teeth showing slightly higher scores on average, the differences were small numerically and the scores were combined for further analysis to increase the sample size.

To assess the replicability of the method for scoring attrition from casts, a second series of photographs was obtained from randomly selected subjects and 20 teeth were re-scored. The mean difference between the two determinations was 0.013 (S.E.=.009), a value which did not differ significantly from zero. In addition the error variance
contributed less than three percent to the observed variance of the attrition scores. Hence the replicability of the methods used for scoring attrition from casts was acceptable and little bias appeared to be introduced by errors.

Scatterplots of the attrition scores against age revealed a non-linear relationship in which attrition increased exponentially with age. Figure 8 demonstrates this relationship for the maxillary first molar in Kalumburu females. Simple transformations were then applied to the attrition scores to impose linearity on the relationship in the manner suggested by Sokal and Rohlf (1969:477). The following transformation:

\[
\text{Transformed score} = 1 + \frac{1}{2} \log_{10} (\text{attrition score})
\]

provided the most consistent linear relationship with age and furthermore the range of transformed scores (from 0 to 1) was preserved (Figure 9). Linear regression equations and correlation coefficients were derived for the relationships between the transformed attrition scores and age, with attrition as the dependent variable.

Estimates of age were derived from observed attrition scores by the inverse prediction method described by Sokal and Rohlf (1969:446), where estimates can be obtained from the rearranged regression equation and confidence limits of the estimate can be calculated. This method was applied to the small sample of casts from Yuendumu to test the reliability of age estimates based on attrition scores.
Results

Table 3 shows the results of the regression analysis for the transformed attrition scores on age for the Kalumburu males and females. Because the Haasts Bluff casts included few male subjects, sex differences were not considered in this group. As expected the transformed attrition scores were positively correlated with age, the coefficients differing significantly from zero (p<.01) for all teeth except the maxillary second molar in males. Examination of the slopes of the regression lines suggested that the rate of wear on first molars was about the same in males and females, but wear on the second molars was more rapid in the females. However, Student's t-test did not reveal any significant sex differences and consequently the data for male and female subjects were pooled to increase sample size.

Regression statistics for the Kalumburu and Haasts Bluff subjects, males and females combined, are shown in Table 4. Limited observations of wear on the second molars in the Haasts Bluff population prevented comparison with the Kalumburu subjects for these teeth but the regression parameters for the maxillary and mandibular first molars did not differ significantly between the two samples. The findings do not preclude the possibility of sex differences or regional variations in the patterns of tooth wear but, within the sampling constraints, it appeared that the two populations could be combined to provide a more reliable, general indication of the relationship between tooth wear and age. Regression statistics for the combined sample are also shown in Table 4 and illustrated in Figure 10a-d.
The reliability of age estimation was assessed by comparing known ages with ages calculated from the observed attrition scores for 10 maxillary molars selected from the test population of Yuendumu Aboriginals. The maxillary first molar was used for the predictions because the correlation between the transformed attrition scores and age was highest for this tooth \( r=0.92 \) and the attrition scores on right and left sides differed, on average, by only 0.02 mm. In addition, from a practical point of view, this tooth is frequently present in skeletal material. The inverse prediction used to obtain these age estimates was:

\[
\text{Age} = 19.1 + (55.6 \times \text{transformed attrition score})
\]

Estimated ages for the Yuendumu test subjects are shown in Table 5.

Estimated and actual ages were highly correlated \( r=0.96 \) but differed, on average, by 4.4 years. Because of the limitations imposed by the small sample size and the constraints of the inverse prediction model, the errors of estimate were high (in most instances, about 12 years). Although the method involved a considerable error component it did assign reliable relative ages to the test subjects. Thus the rank order of estimated and actual ages showed substantial agreement even though the test population differed from the one from which the regression parameters were derived.

Discussion

Previous methods for predicting age from observed dentine exposure have relied on matching wear patterns with established standards (Miles,
or on linear regression models relating age to qualitative attrition scores (Sagne, 1976). The method described by Tomenchuk and Mayhall (1979) and that presented here differ from previous techniques by using quantitative measures based on the extent of cusp reduction or dentine exposure. Tomenchuk and Mayhall used a test sample of 10 dental casts to test their method of age prediction. Actual and estimated ages were highly correlated (r=0.85) and differed on average by about 2 years, but statistically derived confidence limits for their estimates were not given.

Age estimates derived for the Yuendumu subjects were also highly correlated with actual ages (r=0.96). Age was, however, underestimated by an average of more than 4 years, and errors of estimate were high compared with some other age estimation methods. For example, Hanihara and Suzuki (1978) obtained estimates by multiple regression methods relating selected changes in the pubic symphysis to age. In this case the confidence limits were about half those involved in the estimates based on attrition scores.

Despite the relatively broad confidence limits involved, and the constraint imposed by genetic, cultural and environmental differences between the population being studied and the population on which the regression equations were developed, the method appeared to be suitable for the purposes of the present study. In the present instance, the relative ages of subjects were of greater interest than absolute ages, and, furthermore, other established methods of aging were inappropriate for the study population. Age was therefore estimated for each of the Narrinyeri subjects using the inverse prediction equation presented above.
Where both left and right maxillary first molars were present the average of the attrition scores for both teeth was used to predict age. If only one tooth was present age estimates were based on that tooth alone. The age distribution of the 74 Narrinyeri subjects selected for the principal part of this study is presented in Table 6. The mean age of the male subjects was 55.5 years ($s = 11.6$ years) and for females was 52.1 years ($s = 12.6$ years). The calculated age of each subject together with the appropriate confidence limits are included in Appendix 4.
Section Three

DESCRIPTIVE STUDIES
CHAPTER 6

OCCLUSAL ATTRITION

During the industrial revolution technological changes modified the lifestyle of Western populations and consequently dental attrition has come to be considered a sign of dysfunction rather than a result of normal physiological function. Many studies of pre-industrial populations have described the extent or pattern of dental attrition as part of the physical anthropology of the population. As attrition clearly progresses with age, various methods have been developed to obtain age estimates from attrition scores (see Chapter 5). In addition, because the pattern of tooth wear is the result of a direct interaction between the food eaten and the teeth (Walker, 1978), archaeologists and anthropologists have attempted to deduce information about dietary, social and cultural differences between populations from studies of dental attrition. The observed variation in the rate of wear between populations has been considered to reflect important cultural differences (Molnar, 1971a,b, 1972; Smith, 1972, 1976; Walker, 1978; Scott, 1979a).

In his description of the dentition and palate of the Australian Aboriginal, Campbell (1925:116) concluded that:

"The jaws and teeth of the Australian aboriginal are strikingly well formed, with a capacious palate, well shaped arches and large teeth; all of which depict a thoroughly functioning and efficient masticatory system.

The teeth of the Australian ... are probably larger than those of any other living race ...

The symmetrical occlusal and interproximal wear of the teeth ... indicate that the Australian probably effected mastication by regularly alternating lateral excursions of the mandible."
The vitality of the pulp and periodontal membrane was apparently vigorous, as has been shown in the case of the pulp by the remarkable manner in which it physiologically resisted encroachment on its cavity by secondary deposit; and in the case of the membrane by the marked functional stresses it withstood without showing evidence of frequent or general periodontal affections...

The Australian dentition was strikingly free from developmental aberrations and dental disease. The latter, as represented by such universally occurring affections as caries, alveolar abscesses, and periodontal lesions, were conditions almost entirely limited to old age.

The marked immunity from dental diseases would seem to be very closely related with the coarse, tough food which formed their diet and the crude methods of preparation and cooking when such were utilized."

The food preparation methods and dietary habits of the Australian Aboriginals would clearly contribute to the rapid tooth wear seen in these people. Barrett (1969) concluded that:

"Progressive wear of the teeth invariably resulted from the energetic mastication of tough, fibrous foods in which abrasive material was unintentionally incorporated during its collection and preparation...".

Molnar (1972) suggested that:

"...the dietary functions of the teeth are probably the main sources of attrition of the occlusal surfaces. The fibrous nature of the food or its abrasive content has been frequently cited as a major source of tooth destruction, and the preparation, or lack of preparation of food is considered an important factor."

In addition to their masticatory functions, the teeth of many pre-industrial populations were also used to perform a number of non-masticatory functions.
Barrett (1977) described how the teeth were used in "various grasping, biting, piercing, cutting, tearing, shredding, crushing and grinding" operations, many of which would produce significant wear on the occlusal surfaces of the teeth. Where this involved the consistent use of a tooth or groups of teeth to perform some procedure, it is often possible to differentiate between this type of wear and that produced in other ways. If a relatively large object such as a spear point was consistently worked in an area of the mouth it could produce an accelerated and unusual pattern of wear on the teeth involved, resulting in a loss of contact between opposing teeth in that area (Figure 11). On the other hand, the chewing of animal sinew to prepare bindings, the preparation of ochre in the mouth or parafunctional tooth contacts as seen in bruxism (Ramfjord and Ash, 1971), would probably result in a pattern of wear which would be difficult to distinguish from that produced by chewing abrasive food. Whether non-masticatory function contributed to the pattern of wear observed in the Narrinyeri population is not known and would be very difficult to determine.

In this study tooth wear produced by contact between opposing teeth has been described as attrition whether it occurred during mastication, from the use of teeth in some other process, or as a result of parafunctional tooth contact. In cases where obvious non-masticatory factors were involved or attrition had progressed at an unusually rapid rate leading to loss of opposing tooth contact in one region, the observed wear was regarded as abrasion. This simple division was suitable for the present study which was concerned more with observed changes in the teeth than the cause of these changes.
In addition to the descriptive and comparative studies of dental attrition, considerable interest has also been shown in the functional implications of attrition. Begg (1954a,b,c), for example, proposed that many orthodontic problems were related to a lack of arch space, and that this resulted from the decreased attrition seen in modern populations. Klatsky (1939) and Begg (1965) have further suggested that many of the clinical problems facing dentists arise because of this lack of attrition. It has even been advocated that cusps should be reduced in height by grinding to simulate attrition (Murphy, 1968; Berry and Poole, 1976). In addition, studies of the relationship between attrition and facial morphology (Murphy, 1958; Fishman, 1976), temporomandibular joint morphology (Mongini, 1972, 1975; Seward, 1976) and temporomandibular joint pathology (Ficce-Leek, 1972; Moffett, 1974; Seward, 1976; Griffin et al., 1979; Richards and Brown, 1981) have been reported. These studies are summarized in later sections.

Many investigators have referred directly or indirectly to the extensive and rapid dental attrition displayed by Australian Aboriginals but relatively few of these reports are analytical. Campbell (1925) commented on the early age at which areas of dentine became exposed, and described the distribution of attrition scores in a skeletal collection. Subsequently the age distributions were reported for a number of contemporary Aboriginal populations (Campbell and Moore, 1930; Campbell and Gray, 1936; Campbell, 1937, 1938a,b,c). Information from these studies was combined in a description of the jaws and dentition of the Australian Aboriginal where Campbell (1939) concluded that:
"...from early adult life to middle age attrition is more marked in females than in males. This is probably due to the fact... that the menfolk are essentially the hunters, the womenfolk the gatherers. It seems obvious... that the womenfolk would naturally tend to consume a greater proportion of the type of food they spend their time collecting. These are, in particular, those vegetable foods which are pulled or dug up from the ground; and in eating such foods considerable sand and grit is chewed as well. Then in the distribution of meat foods women generally receive their share of the tougher and more sinewy part of the carcase. Thus the more marked wear of the females' teeth is rather expected."

Similarly, Heithersay (1960) and Barrett, Brown and Macdonald (1963) have also described more rapid wear in Australian Aboriginal females and evidence presented earlier (Chapter 5) suggested a similar tendency in some central and northern Australian populations.

Both inter-jaw and inter-molar gradients in tooth attrition scores have been reported for Australian Aboriginals by Murphy (1959b) and Lavelle (1970). They reported a similar pattern of gradients except in comparisons involving the maxillary third molars where the differences observed by Murphy were relatively larger. By comparing gradients between populations Lavelle has shown that Australian Aboriginals display attrition rates as great or greater than the most rapid rates observed in other pre-industrial populations.

One of the principal problems in the study of dental attrition has been the lack of a suitable method for quantifying the condition. Most studies have used simple ordinal scales to assess the extent of occlusal tooth wear. Broca (1879) classified patterns of dental wear as:
1. Enamel worn without cusp obliteration or dentine exposure;
2. Cusps worn to the extent of dentine exposure;
3. Appreciable wear of tooth crown with obliteration of occlusal surface features;
4. Excessive wear resulting in substantial reduction in the crown portion of the tooth toward the neck region.

Many subsequent studies have used Broca's scale or minor modifications of it, applying the criteria to individual teeth or, by assigning one score for a subject, to the entire dentition (e.g. Leigh, 1925; Campbell, 1925; Goldstein, 1932; Davies and Pedersen, 1955; Moorrees, 1957; Lysell, 1958; Ramfjord, 1959; Heithersay, 1960; Barrett, Brown and Macdonald, 1963; Brothwell, 1963). Recently ordinal scales with more categories have been developed to describe stages in the progressive reduction of the tooth crown. For example, Murphy (1959a) described 7 different stages in the progressive exposure of dentine for anterior teeth and 9 stages for posterior teeth. Also, Molnar (1971a) described eight stages for both anterior and posterior teeth. By dividing each molar tooth into four quadrants and scoring each quadrant on a 0 to 10 scale, Scott (1979b) provided a 40 point scale for the assessment of molar attrition. Ordinal scales which rely on the matching of patterns of enamel wear and dentine exposure, no matter how extended, offer only a qualitative assessment of the extent of attrition, rather than a quantitative measure of tooth reduction.

To quantify the extent of dental attrition, Tomenchuk and Mayhall (1979) measured molar cusp heights and related these to crown diameters in the manner described in Chapter 5. While this method has a number of advantages, cusp height is reduced to zero at a relatively early age in populations showing rapid tooth wear, limiting the value of the method in groups such as the Narrinyeri. - 50 -
When dentine exposure is common, the area of exposed dentine can provide an indication of the extent of attrition. Behrand (1977) measured the areas of exposed dentine and total crown areas and used the ratio of the two as a measure of the extent of attrition. Walker (1978) used a similar method, considering absolute areas rather than ratios, in a comparative study of attrition rates between populations.

While cusp heights and areas of exposed dentine both provide a method for the quantitative assessment of the extent of occlusal attrition, neither can assess wear at both extremes of the scale or be easily related to the actual amount of tooth tissue removed. Nevertheless compared with even the most complex ordinal scales they offer objective, qualitative assessments of the extent of wear.

Because attrition scores are clearly age-related, most interest has been directed toward descriptions of the rate of attrition. In early studies, tables describing the distribution of scores in various age groups were presented (Campbell, 1925; Leigh, 1925). Individual subjects of known age could then be compared with the total population to determine if the observed extent of attrition was typical for subjects of that age. Alternatively, the distribution of scores in different populations could be compared to obtain an indication of relative rates of attrition.

Smith (1972) suggested that relative rates of tooth wear might best be studied by considering gradients in scores for the molar teeth. Because the eruption times of the first two permanent molars show very small interpopulation variation (Fanning and Moorrees, 1969), the differences between attrition scores for first and second molars should
reflect the amount of tooth wear occurring in a fixed time period. If it is assumed that this difference is preserved by the scoring method, the observed differences between first and second molar scores should reflect the rate of attrition for the population. Smith considered the correlation coefficient between first and second molar scores to indicate the rate of wear for the population but, as Scott (1979a) suggested, this was more an indication of the variation in the differences in scores between subjects within a population.

More recently Smith (1976) suggested that molar scores should be related by linear regression. While the slope of the regression line would provide an indication of the rate of wear, it is not clear which variables should be considered as dependent or independent, as neither can be assumed to be free of measurement error.

A new approach to the problem has been suggested by Scott (1979a). To overcome the objections to the use of linear regression analysis, she has suggested that the principal axis method described by Sokal and Rohlf (1969:526) should be used to relate attrition scores for pairs of teeth. Whereas the linear regression model assumes that all deviations from the regression line arise from variation in the dependent variable, the principal axis method considers deviation measured perpendicular to the axis itself (Figure 12). The line obtained by this method represents the major axis of the ellipse formed by the two dimensional distribution of scores for the two variables \(X\) and \(Y\). The equation of the principal axis is:

\[
X = \bar{X} + b_1 (Y - \bar{Y})
\]

where \(X\) and \(Y\) are paired measures of variables with means of \(\bar{X}\) and \(\bar{Y}\) respectively, and the slope of the axis \(b_1\) is calculated as:
\[ b_1 = \frac{s_{XY}}{\lambda_1 - s_X^2} \]

where \( s_X^2 \) is the variance of the variable \( X \), and \( s_{XY} \) is the covariance derived in the usual way and \( \lambda_1 \) is the first eigenvalue:

\[ \lambda_1 = \frac{1}{2} \left[ s_X^2 + s_Y^2 + \sqrt{(s_X^2 + s_Y^2) - 4(s_X^2 s_Y^2 - s_{XY}^2)} \right] \]

This eigenvalue is a measure of the variability along the principal axis. The distribution ellipse also has a minor axis perpendicular to the major axis and a second eigenvalue:

\[ \lambda_2 = \frac{1}{2} \left[ s_X^2 + s_Y^2 - \sqrt{(s_X^2 + s_Y^2) - 4(s_X^2 s_Y^2 - s_{XY}^2)} \right] \]

The slope of the principal axis represents the relative rate of exposure of dentine for a pair of teeth and therefore a comparison of these slopes between groups provides an indication of the relative rates of wear in different populations.

**Methods**

To provide an accurate representation of the pattern of attrition for the Narrinyeri population, all subjects with 6 or more measurable teeth (84 males and 72 females) were included in this part of the study. Because of the advantages of quantitative methods of assessment, an attrition score was derived for each tooth by the method outlined by Behrand (1977). Colour transparencies of each dental arch were obtained with the specimens orientated to ensure that the occlusal plane and the
focal plane of the camera were parallel. This was achieved using a simple spirit table (Figure 13). A relatively large camera to object distance (1.25 metres) was selected to minimise the effect of differential enlargement due to the curvature of the occlusal plane (Gavan, Washburn and Lewis, 1952). A millimetre scale and identification information were included in each photograph (Figure 14a).

These transparencies were projected using a specially constructed viewing box to ensure that the path of projection remained orthogonal to the screen and to ensure a constant enlargement of approximately 16 times.

Images were traced onto paper using a rapidograph pen with a tip diameter of 0.5 mm to record the outline of the dental crown and areas of exposed dentine (Figure 14b). Image enlargement was recorded by measurement of the scale included in the photograph. The tracings were checked by projecting the transparencies at an enlargement of about 40 times, and comparing the image with the tracings. Where any discrepancies were detected transparencies were traced a second time.

Areas were then measured from these tracings with a Hewlett Packard 9874A digitizer programmed for use as a planimeter. The ratio of the area of exposed dentine to the total crown area was calculated automatically under programme control.

To assess the significance of the errors involved in scoring attrition by this method, a series of 20 randomly selected subjects were re-examined several months later and a second series of photographs obtained. These were projected, traced, measured and checked and the measurements compared with those obtained earlier.
In general, the differences between measurements obtained on the first and second occasions were small (Table 7). The mean differences (first - second measures) ranged from -0.038 for the maxillary left central incisor to +0.026 for the maxillary left second molar. In only 2 cases (maxillary right first premolar and maxillary right first molar) were the differences significantly greater than zero (p<0.05). In these instances the standard errors of the differences were small suggesting a narrow range of differences between the two determinations. For 18 of the 32 teeth the mean difference was no greater than 0.010 representing a 1 percent difference in the assessment of exposed dentine area relative to crown area.

On average measurement errors contributed only a small proportion to the total observed variance in attrition scores (mean = 2.0 percent; standard deviation = 2.5). The contribution of errors to the total variance ranged from 0.1 percent for maxillary left canines and mandibular left central incisors to 10.4 percent for the maxillary left central incisor. In a number of cases where the error appeared relatively large, the sample size was small due to missing teeth.

To provide a summary of the relative rates of wear for each tooth, equations of the principal axes relating scores for each tooth to scores for the maxillary first molar were calculated by the methods described previously. The maxillary first molar was chosen as the reference tooth because:
1. It was frequently present in museum specimens;
2. It erupted at an early age;
3. Attrition scores for the maxillary first molar showed a high degree of symmetry for both males and females;
4. In this study the maxillary first molar had already been selected as a reference for age estimation.

Before calculating the equations of the principal axes, scatterplots of attrition scores for each tooth against the maxillary first molar were examined to identify outlying subjects for re-examination. Where the large deviations in scores could be explained by some obvious non-masticatory factor such as the absence of opposing tooth or the presence of crown fractures, teeth were excluded from the study. In addition, teeth showing no exposed dentine (score = 0.0) or total loss of enamel (score = 1.0) were excluded. This was necessary because the distributions of scores were truncated at each extreme. For example the maximum score of 1.0 indicated that the last remnant of enamel had been worn away, irrespective of any additional dentine loss through continuing wear. The inclusion of extremely worn teeth with the maximum attrition score of 1.0 would produce a scatter of scores around this point on the scale, blasing the estimation of the principal axis and reducing the measure of covariance between the teeth concerned.

Equations of principal axes relating scores for each tooth to maxillary first molar scores were calculated using a modified version of the program "MOMENT" provided by Sokal and Rohlf (1969:700) which is described in Appendix 2. The slopes of these axes provided an indication of the rate of exposure of dentine for the tooth concerned relative to the rate for the first molar. The intercept of the principal axis with the Y-axis reflected the relative timing of the first appearance of dentine for the teeth being considered.
Scott (1979b) used the slopes of the axes relating the molar attrition scores to compare relative attrition rates in different populations. In the present study, the axes have been used in a slightly different way to compare observed attrition scores for an individual with the pattern for the population. Expected attrition scores for each tooth, based on the observed score for the maxillary first molar, were generated using the equations of the principal axes. For example, if the equation relating scores for the maxillary and mandibular first molars was:

\[ \text{MAN.M1} = 0.05 + 1.34 \times \text{MAX.M1} \]

where \text{MAN.M1} and \text{MAX.M1} are the attrition scores for the mandibular first molar and the maxillary first molar respectively, expected scores could be calculated by substituting observed scores for maxillary first molar attrition into the equations. The difference between the observed and expected scores for each tooth, termed the residual attrition score (residual = observed - expected), provided several types of additional information.

Firstly, the pattern of residual scores could be used to assess the accuracy with which the principal axis model described the data. If the mean of the residual scores for any tooth differed significantly from zero, with estimated scores being consistently positive or negative, the model was probably inappropriate for that particular tooth. This might have occurred, for example, when the relationship was not truly linear. In addition, the scatterplots of residual scores against both actual and expected scores were examined. The patterns of these plots also provided information about the validity of the model. As residuals should be randomly distributed, a significant correlation between
residual scores and either actual or observed scores would suggest that the axis did not fit the data well. Similarly, an increase in the spread of residuals at higher attrition scores would imply that the variance of the residuals increased with increasing attrition scores and that one or both variables should have been transformed in some way (see Seber, 1977:164).

The presence of consistent differences in the pattern of wear between selected groups could also be assessed from the distribution of residual scores for the groups. For example, in the present study the equations of the principal axes were calculated with the male and female groups combined. Sex differences in the rate of attrition could be assessed by comparing the mean residual scores for males and females. If any tooth was wearing more rapidly in one group than in the other, a difference in the mean residual scores should be seen. Furthermore, attrition scores for each individual could be compared with the pattern for the population.

There are a number of advantages in analysing data in this way, but the principal axis method was not without its limitations. For example, it was necessary to assume that the rate of wear of the reference tooth, in this case the maxillary first molar, was constant between groups. Evidence provided earlier (Chapter 5) suggested that this might be a reasonable assumption, however if this was not so, observed differences in residual scores between groups might have arisen as a result of differences in the rate of wear of the reference tooth rather than from actual differences.

Secondly, the use of many bivariate comparisons to describe the population was not ideal but was necessary because of the relatively
large number of missing teeth in the population. The majority of the 74 subjects to be examined in detail later had between 20 and 25 teeth present (Table 8). If all teeth had been present the model could have been extended from 2 dimensions to 32 and a principal components analysis used. However this was not possible and so, for the purposes of the present study, the application of a series of principal axes to describe the relationships between attrition scores and to provide expected scores from which residuals could be calculated, appeared a satisfactory alternative.

Results

The distribution of attrition scores for the total Narrinyeri sample of 156 subjects is shown in Table 9. In general, the mean attrition scores for males tended to be slightly greater than those for females. Considered independently of age, however, they provide little information about the patterns or rates of attrition.

Both the mean differences and the intra-class correlations between scores for left and right sides suggested that, in general, the pattern of wear was relatively symmetrical. For females the mean differences between left and right sides were small (Table 10). The largest differences were in the mandibular anterior teeth of males, where scores for the left side tended to be slightly greater than for the right. However, only in the case of the mandibular canine was this difference significant (p<0.01).
The correlations between scores for left and right sides reflected the same tendency for males to show a slightly less symmetrical pattern of wear than females (Table 11). In three cases (maxillary central incisor and second premolar and mandibular first molar), female correlations were significantly larger than male correlations, but for some teeth (eg. maxillary first premolar and second molar and mandibular lateral incisor) the male coefficients were as great or greater than those for females.

For the 70 individuals for whom 6 or more tooth pairs were available, the mean difference between scores for left and right sides was calculated from the available pairs of teeth. The distribution of these differences is shown in Figure 15. Ten of these subjects (14.3 percent) showed significant differences between sides. Of these, 5 were male (13.9 percent of the male sample) and 5 female (14.7 percent of the female sample). In 7 of these cases the score for the left side exceeded the score for the right while in 3 cases scores for the right were greater. Although some subjects showed relatively large variations in score between sides, in the majority of cases the differences were small. Only in the extreme cases did the observed patterns of wear appear asymmetrical on inspection (Figure 16).

Similarly, the intra-class correlations between the available pairs of teeth tended to be high, with only 4 of the 71 available subjects (5.6 percent) showing correlation coefficients less than 0.60 and the majority (50.7 percent) showing correlations greater than 0.80 (Figure 17). Again, the dental arches of the few subjects with extremely low correlations between pairs of attrition scores appeared asymmetric, while the pattern of wear appeared symmetrical for the majority of subjects (Figure 18).
The principal axes which described the rates of dentine exposure for each tooth relative to the maxillary first molar, were calculated from scores for left and right sides and for male and female subjects combined (Table 12). The correlations between scores for each tooth and the maxillary first molar suggested that the strength of this association diminished with distance from the reference tooth, with the mandibular first molar showing the highest correlation and the maxillary central incisor and third molar the lowest.

To assess the suitability of the model, the distributions of the residual scores for each tooth were examined (Table 13). For 5 teeth (maxillary lateral incisor and third molar and mandibular central and lateral incisors and third molar) the mean of the residual scores differed significantly from zero (p<0.05), suggesting that the linear model employed was not entirely adequate for these teeth. Plots of residual scores against both actual and expected scores did not reveal any obvious trends in residuals (eg. Figure 19), suggesting that with the exception of the extreme anterior and posterior teeth, the principal axis model provided an acceptable explanation of the observed pattern of attrition.

When the distributions of residual scores for males and females were compared (Table 14), significant differences were evident. With the exception of the maxillary anterior teeth, the mean residual scores were consistently greater for females than for males. This suggested that the rate of attrition for females tended to be greater than for males, although only in the case of the mandibular second premolars was this difference significant. In general the residual scores for males, while
smaller than those for females, showed much greater variation. The variances of the residuals were greater in males for all teeth except the mandibular lateral incisors and first molars; the sex differences in variances were significant for the maxillary lateral incisor, canine and second premolar and for the mandibular canine and second molar, and tended to be greater for all other teeth except the mandibular lateral incisors and first molars.

Discussion

With the exception of the teeth most distant from the maxillary first molar, the principal axis model appeared to provide a satisfactory representation of the relationship between attrition scores. If the assumption that the rate of wear of the maxillary first molar was approximately equal in males and females is correct, then the distribution of residual scores suggests that females tended to show a more rapid rate of tooth wear than males for all but the maxillary anterior teeth. This supports the conclusions reported by Campbell (1939), Heithersay (1960), Barrett, Brown and Macdonald (1963) and Molnar, McKee and Molnar (in press), all of whom reported a more rapid rate of tooth wear in Australian Aboriginal females.

Because the present analytical methods have not been applied previously to analyse patterns of attrition previously, it is not possible to compare the rate of attrition in this population with that reported for other groups. Based on previous reports, however, it is clear that Australian Aboriginals show a very rapid rate of dental attrition.
While Beyron (1964) described a symmetrical pattern of attrition in Australian Aboriginals, no quantitative analyses of symmetry in attrition are available. Therefore, it is difficult to decide whether the observed pattern of wear should be described as symmetrical or asymmetrical. The mandibular canine in males was the only tooth which showed a significant mean difference between left and right sides, and even then the difference was relatively small (mean difference = -0.055). The average total crown area for the mandibular canine was about 40 mm$^2$ (for males = 43.9 mm$^2$ (right), 43.5 mm$^2$ (left); for females = 38.3 mm$^2$ (right), 37.7 mm$^2$ (left)) so that a difference of 5.5 percent represents about 2 mm$^2$. Differences of this magnitude are illustrated in Figure 20; clearly they are difficult to detect.

When individual subjects were considered, both mean differences and intra-class correlations between attrition scores for available pairs of teeth revealed marked asymmetry in tooth wear for only a few subjects. In most cases, however, the mean difference between sides was small and the correlation between sides high; furthermore, the pattern of wear was clearly symmetrical.
Variation in dimensions of the dental arches is conditioned by the size and arrangement of teeth as well as the morphology of the palate and mandible. Although the heritability of tooth size in Australian Aboriginals has been described (Townsend and Brown, 1978), the relative contributions of genetic and environmental factors to arch size and shape are not known.

Experimental animals fed on a hard diet have been shown to have relatively large dental arches (Watt and Williams, 1951) but many believe that environmental factors are relatively unimportant in determining arch sizes (e.g. Brodie, 1948). The tendency for evolutionary reduction in the size of the facial structures is reflected in dental arch dimensions, which have been shown to be larger in pre-industrial populations than in more modern groups (Lundström and Lysell, 1953; Goose, 1962).

Turner (1891) was probably the first to describe dental arch dimensions of Australian Aboriginals in detail; after comparing measurements of a series of Aboriginal crania with those from a European population, he concluded that:

"... both in European and Australian skulls the upper dentary arcade, with some rare exceptions, is wider than the lower at the 1st. and 2nd. molars; but that in Europeans the excess of width is as a rule, not so marked as in the Australians ... (and) ... in the European skulls the absolute width at the molar crowns was much less than in Australians."
Where comparisons between previously reported studies were possible they confirmed that arch dimensions of Australian Aboriginals were at least as large as other pre-industrial populations, and larger than those reported for modern groups (Barrett, Brown and Macdonald, 1965; Lavelle, Foster and Flinn, 1971).

The relatively large difference in breadth between the maxillary and mandibular arches described by Turner (1891) may have arisen in a number of ways. Turner's original belief was that it reflected the relatively large tooth size in Australian Aboriginals. Barrett (1958) suggested that the observed differences may be an "expression of inherited differences in size, shape and relation of upper and lower dental arches" especially if the factors acting to determine maxillary and mandibular arch dimensions were acting independently. In addition, he proposed that the observed differences could reflect compensatory changes occurring at the time of eruption and alignment of the relatively large maxillary incisors, or simply the tendency for maxillary alveolar growth to be directed downward and outward and mandibular alveolar growth to be directed upward and inward. In each of these cases the removal of interlocking cusps by attrition would facilitate development of the observed differences. Barrett also proposed that:

"The occlusion of the obliquely worn masticatory surfaces possibly results in tooth movement in a manner similar to the action of bite planes used for orthodontic purposes. Masticatory forces thus applied may cause, or contribute to, expansion of the upper dental arch and may limit lateral expansion of the lower dental arch and bring about a relative difference in arch width."
These relatively large differences in arch breadth are reflected in the unconventional coronal arch relationship seen in some Australian Aboriginal subjects. Barrett (1953) described the tendency for Australian Aboriginals to show a marked discrepancy between maxillary and mandibular breadths to the extent that they could not occlude their teeth in a position of maximum interdigitation on both the left and right sides at one time. About 25 percent of subjects showed this pattern (Barrett, 1969). Because these individuals alternated between their left and right intercuspal positions during function, he described the pattern as "alternate intercuspation" (Barrett, 1958).

As with other linear dimensions, dental arch dimensions have been found to be significantly larger in males than in females. Both Heithersay (1961) and Barrett et al. (1965) reported arch breadths, measured between the buccal surfaces of molars, which were between 3.0 and 5.0 mm larger in males than in females.

Conflicting reports have dealt with the effect of continuing tooth attrition on dental arch breadths. Campbell (1925) described a consistent increase in the breadth of both maxillary and mandibular arches between his young adult and adult groups. The largest difference between the means (2.7 mm) was observed for both maxillary and mandibular second molars, and the smallest increase (0.8 mm) was seen in the first molar area in the mandibular arch. Murphy (1964a), in considering the relationship between arch breadths and attrition, did not find any significant change in arch breadth in the maxillary first molar area. He observed, however, a slight increase in arch breadth in the maxillary third molar region. The mandibular arch showed a significant increase in breadth at the first molar and a highly significant increase in the region of the third molar. In addition,
Murphy found that these differences were sex specific:

"In the skulls selected as female there was no significant change in either maxillary or mandibular arch widths with increasing attrition. In those selected as male, while there was no significant change in maxillary arch widths, in the mandible there was a significant increase in arch width at M1 and a highly significant one at M3."

In contrast Heithersay (1961) found consistent small decreases in arch breadths with increasing age in both males and females. Therefore, the precise nature of the relationship between age and arch breadth is not clear.

There is evidence of a degree of coordination between maxillary and mandibular arch breadths. Knott (1961), Barrett et al. (1965) and Solow (1966) described relatively high correlations between maxillary and mandibular arch breadths, and the first two of these reports indicated that these correlations increased from adolescence to adulthood. Barrett et al. reported correlations between maxillary and mandibular arch breadths measured at the second molars ranging from 0.85 to 0.92 in young adult Australian Aboriginals showing relatively little attrition.

In previous studies dental arch dimensions have been measured by one of two methods depending on the purpose of the study. Either anthropometric measurements of the maximum distances between the buccal or lingual surfaces of premolar and molar teeth have been recorded (eg. Campbell, 1925; Heithersay, 1961; Barrett et al., 1965; Lavelle et al., 1971) or odontometric measurements of distances between dental reference points have been made (eg. Moorrees, 1957). While anthropometric arch dimensions defined in this way are easily obtained, they reflect not
only arch size but also tooth size, which can complicate the analysis in some cases. Measurements of the distance between reference points determined by fossae of teeth or cusp tips offer advantages, especially where the contact relationships between upper and lower teeth follow classical patterns. However, in populations where dental attrition is common, reference points on occlusal surfaces are often poorly defined, limiting the value of odontometric methods.

In addition, these methods do not necessarily detect important differences between the dimensions of the maxillary and mandibular arches. Difficulties can occur even when the distances between structures which are usually functionally related, such as the central fossae of mandibular molars and the mesio-palatal cusps of maxillary molars, are considered. Although the classical concepts of dental articulation suggest that reference points such as these should be closely associated with the teeth in contact, many individuals show small deviations from this expected pattern and some will show very marked differences. For example, in subjects with disto-occlusion of the mandibular dental arch (Angle Class II), the difference between the inter-fossa distance in the mandibular arch and the inter-cusp distance in the maxillary arch might be small or even negative, but the observed difference in arch breadths may be similar to that in subjects with a normal arch relationship. This apparent discrepancy is consequent upon corresponding arch breadths in maxilla and mandible being defined in different antero-posterior planes. Attempts to compensate for these differences introduce additional variables and a number of technical difficulties.
Methods

Dental arch dimensions recorded in this study were required for the investigation of the relationship between arch breadths and the direction of wear of the molar occlusal surfaces, rather than for purely descriptive or comparative purposes. Therefore, the approach employed was different from that described by other investigators.

To ensure that maxillary and mandibular arch breadths were measured in the same frontal plane, the tracings used to assess attrition were superimposed. To reproduce the antero-posterior arch relationship, the incisor overjet and the horizontal distances between the distal surfaces of the most posterior maxillary and mandibular teeth were measured from the lateral cephalometric radiographs. In a similar way, information from the antero-posterior radiographs assisted in establishing the correct buccal overjet.

With the tracings superimposed, the centroid of each mandibular tooth was marked after visual inspection of the traced tooth outline. To avoid the effect of differences in tooth size on the arch dimensions, the distance between both the buccal surfaces and the lingual surfaces of mandibular molar pairs was recorded in the line of the centroids of pairs of teeth, and the mean of these two measurements was taken as the arch breadth following the method described by Lavelle et al. (1971). The breadth of the maxillary arch was measured in a similar way, but in the plane of the centroids of the superimposed mandibular teeth rather than in the plane of their own centroids (Figure 21). While arch breadths in the maxilla were not measured across corresponding areas of the teeth for each subject, consideration of some of the extreme cases suggested that this did not introduce any significant bias. Where the
centroid of the mandibular tooth was superimposed on the contact area of two maxillary teeth rather than on a single tooth, the midpoint of the contact area was take to indicate the arch breadth.

In each case a midline was constructed on tracings by marking points midway between each available pair of mandibular first, second and third molars and the midpoint between the incisors, and constructing a line to pass as near as possible to each of these points. Where one of a pair of molars was missing, twice the distance from the available tooth to the constructed midline was taken as an indication of the arch dimension. Because maxillary and mandibular arch breadths were measured in the same frontal plane, arch breadth differences obtained by subtracting upper and lower arch breadths were not influenced by variations in the antero-posterior relationship between maxillary and mandibular arches.

To assess the significance of the errors involved in the measurement of arch breadths by this method, 20 randomly selected subjects were re-assessed some months later. Data were obtained from a second series of photographs and the results of first and second measurements compared. Mean differences in maxillary arch breadths were generally positive, ranging from 0.31 mm to 0.37 mm, suggesting that, on average, the second measurement of arch breadth was slightly smaller than the first (Table 15). In contrast, the mean differences in mandibular arch breadths were negative, suggesting that second measures were generally larger than those obtained on the first occasion. Although the mean differences were never larger than 0.5 mm, the first and second measurements differed significantly from zero in the area of the mandibular first and third molars. This was partly due to the small standard error associated with these differences. The standard errors
were probably smaller than for the maxilla because the reference points defining these measurements were derived from the mandibular teeth, and did not include the errors incurred in superimposing tracings.

The errors involved in superimposing the maxillary and mandibular tracings probably also explain the slightly higher proportion of the observed variance of maxillary breadths attributable to errors. This contributed between 1.3 and 5.2 percent of the total variance in mandibular arch breadths, compared with between 1.9 and 10.3 percent in the case of maxillary breadths.

Results

The distributions of maxillary and mandibular arch breadth measurements for males and females are presented in Table 16. In each case the mean arch breadth was significantly larger in the males. The differences were generally larger posteriorly than anteriorly suggesting some sex differences in dental arch shape.

There was no evidence of any significant changes in arch dimensions with age. The tendency was for weak negative correlations between arch breadths and age for all but the maxillary second and third molar region in males. No correlation coefficients differed significantly from zero (Table 17).

The relationships between attrition and arch breadths were stronger, however (Table 18). For females, maxillary arch breadths were generally negatively correlated with attrition, suggesting that
maxillary arch breadth tended to decrease with advancing attrition. The pattern was less consistent in the mandible, where correlations tended to be negative but were generally weaker. The pattern for males was not as clear as for females. If only significant correlations were considered it appeared that arch breadths increased in the maxillary first molar and mandibular third molar areas, and decreased in the mandibular first molar and maxillary third molar areas. However, these correlations were generally weak.

The correlations between maxillary and mandibular arch breadths were generally lower than those reported in other studies (Table 19). For males, the correlation coefficients were smallest in the first molar region and largest in the plane of the third molars. For both first and second molars, correlations tended to be higher for females than for males but in the case of the third molar the opposite trend was evident.

Dental arch breadth differences were largest in the plane of the first molar and smallest in the third molar area in both males and females. The mean difference in the first molar area for males was almost identical to that reported by Turner (1891) for his predominantly male sample of Australian Aboriginals. Arch breadth differences were consistently larger in males than in females (Table 20). The variation between male and female arch breadth differences was smaller on average in the first molar area (1.3 mm) than in the third molar area (2.0 mm). In addition, for females the arch breadth difference tended to be negative in the third molar region for females (mandibular breadth greater than maxillary breadth) whereas for males the difference tended to be positive (maxilla greater than mandible). No significant correlations between arch breadth differences and age were detected (Table 21).
For females especially, arch breadth differences in the first molar area and to a lesser extent in the second molar area, decreased with advancing attrition (Table 22). This reflected the relatively larger reduction in maxillary arch breadth in this region in females. For males, differences in arch breadth in the first molar area changed only slightly with advancing attrition. The tendency for the maxillary arch to decrease in breadth and for the mandibular arch to increase in breadth in this region probably explained the generally negative correlations between arch breadth differences and attrition in the first and second molar areas in males. Arch breadth differences in the third molar area in females and the second and third molar areas in males did not appear to change in any consistent way with advancing attrition.

Discussion

From previously published data it is clear that dental arch dimensions in Australian Aboriginals were at least as large as, and often larger than, those reported for other pre-industrial populations and were clearly larger than those reported for modern groups. As with other linear dimensions, arch breadths were significantly larger in males than in females. The differences between maxillary and mandibular arch breadths were also larger in males than in females. In addition, arch breadth differences decreased posteriorly from the first molar to the third molar. For females, mandibular arch breadth in this region was, on average, larger than the corresponding maxillary dimension whereas the maxilla was broader than the mandible in the third molar area for males and for both sexes in the first and second molar areas.
The observed differences in the relationship between arch breadths and age could reflect differences in arch shape between populations. For example, if the molar segments were relatively parallel, arch breadths would not decrease significantly, even with extreme interproximal attrition and mesial migration. Although the arch breadth measurements reported by Heithersay (1961) were recorded in a different way to those reported here, comparison of mandibular arch breadths, for example, suggested differences in arch shape between the Haasts Bluff group and the Narrinyeri population. For the Narrinyeri, the differences between the arch breadth measured at the first molar and at the second molar were smaller (males = 5.7 mm; females = 4.9 mm) than for the Haasts Bluff group described by Heithersay (males = 6.5 mm; females = 5.5 mm) suggesting that the mandibular buccal segments tended to be more parallel in the Narrinyeri group. As a result, greater arch breadth decreases with age may have been expected in the Haasts Bluff group than in the Narrinyeri group where molar segments were more parallel.

The tendency for arch breadths in the first molar area to decrease with advancing attrition, as described by Murphy (1964a), was also evident in the Narrinyeri females. Murphy found that in males the mandibular arch breadths increased significantly while the maxillary dimensions increased only slightly. In contrast, the Narrinyeri males showed only a very weak tendency for arch breadths to increase with attrition, and then only in the maxillary third molar and mandibular first molar areas. In the maxillary first molar and mandibular third molar areas, arch breadths tended to decrease with advancing attrition.

The relatively low correlations between maxillary and mandibular arch dimensions observed in this study might result from the more
extensive attrition seen in the Narrinyeri population. The higher correlations reported by Knott (1961), Barrett et al. (1965) and Solow (1966) were based on measurements of populations showing relatively little attrition. In addition, the use of variables defined by precise cusp to fossa relationships between maxillary and mandibular teeth probably led to a higher degree of association between arch breadths. Certainly within the Narrinyeri population (with the exception of the mandibular third molars in females) correlations were lower for teeth showing higher average attrition scores than for teeth showing lower scores.

Because of the number of factors involved in dental arch development, a complete understanding of the determinants of dental arch size and shape and of the relationship between age and arch dimensions will probably accrue only when detailed longitudinal studies of arch dimensions are complete.
Monson (1932) believed that in a well-adapted dentition the occlusal plane conformed to the surface of a sphere 4 inches in diameter. The mandibular condyles were also said to fall on the same sphere. This precise configuration is rarely seen, however, and the orientations of the occlusal surfaces of the teeth vary considerably between individuals depending on many determinants. For example, variations in the angulation of the crown relative to the root, and the paths of tooth emergence will affect occlusal surface orientations. Changes in the occlusal plane may also result from tooth attrition or from the movement of teeth within the alveolar bone.

In populations showing relatively extensive attrition, the orientation of the occlusal plane when viewed in the frontal plane changes from anterior to posterior teeth. In the mandible, for example, the premolars and first molar tend to display a buccal orientation while the third molar tends to retain a lingual inclination (Figure 22).

Knowles (1915) first observed a "twisted" occlusal plane in Canadian Eskimos and since then this has been described in many populations (for example, Neumann, 1922:577; Campbell, 1925; Muller, 1925; Drennan, 1929; Dart, 1929; Oranje, 1934; Pleasure and Friedman, 1938; Moses, 1946; Ackermann, 1963; Beyron, 1964; van Reenen, 1964; Murphy, 1964a). Tobias (1980) has recently reviewed much of this earlier work.
Ackermann (1963) claimed to have independently discovered the phenomenon in 1933, when he described the continually changing orientation of the occlusal surface of the posterior teeth as a "helicoidal plane". Much of the terminology used to describe occlusal plane morphology was introduced by Ackermann. He described the region where the direction of the occlusal surfaces changed from a buccal to a lingual orientation as the pas helicoide, and described occlusal surfaces directed toward the palate in the maxilla and the reciprocal buccally-orientated planes in the mandibular arch as ad palatum. He classified the opposite situation, with surfaces directed buccally in the maxillary arch and lingually in the lower arch as ad lingum, while he called the flat occlusal plane ad planum (Figure 23).

Over the years a number of explanations for the development of the helicoidal occlusal plane have been offered. Neumann (1922), who first described the occlusal plane in Australian Aboriginals, suggested that the helicoidal pattern resulted from differences in the orientation of the dental crowns relative to the occlusal plane but this view has not been widely supported. Pleasure and Friedman (1932) believed that the direction of tooth eruption tended to produce the curve described by Monson (1932), and that attrition modified the direction of the occlusal plane. They suggested that the effect of attrition was less marked posteriorly because the food bolus was rarely chewed on the more posterior teeth. Therefore, these teeth frequently maintained their original orientation. Van Reenen (1964) also believed that the initial lingual orientation of the mandibular tooth crowns was less marked anteriorly and in addition that the anterior teeth moved further than the posterior teeth during lateral excursions of the mandible. This resulted in less posterior wear and exaggerated the original differences in crown orientations.
The explanation offered by Campbell (1925) was probably the simplest. He believed that the helicoidal pattern of wear could be explained in terms of differences between maxillary and mandibular arch breadths. He observed a relatively larger arch breadth difference in the first molar area, resulting in heavier wear on the maxillary palatal cusps than on the mandibular buccal cusps. This tended to reverse the original orientation of the occlusal plane. However, in the third molar area the mandibular arch was often as wide or even wider than the maxillary arch and as a result the tendency in this region was for buccal and lingual cusps to show at least equal wear and in some instances for wear to be greater on the buccal cusps of the maxillary teeth and the lingual cusps on the mandibular teeth.

Although changes in the orientation of the occlusal surface with the progress of attrition have often been described, few attempts have been made to quantify these changes. The few metric studies reported provide conflicting evidence on the changes that occur with time and advancing occlusal attrition.

Murphy (1964a) found that the orientation of the occlusal surface of the mandibular first molar became more buccal with advancing attrition, while the direction of the third molar remained virtually unchanged. He explained this in terms of the different "attritional stress" to which the first and third molars were subjected, observing that wear on the first molars was the result of activity on the chewing side while wear on the third molars arose from contact on the non-chewing side (Murphy, 1964b). Similarly, Hall (1976) found that for both the maxillary first and second molars, the direction of the occlusal plane changed significantly with the progress of attrition while the
direction of wear on the third molars was not related to the extent of attrition. She explained this in terms of observed arch breadth differences between the first and third molar regions.

After considering age changes in the orientation of the occlusal surface, Butler (1972) concluded that "... continual wear would result in mandibular teeth with an entirely buccal slope of the occlusal surfaces and maxillary teeth with an entirely lingual occlusal surface". The exact relationship between attrition and the direction of the occlusal surface is therefore unclear.

A number of methods have been developed to assess the direction of wear of the occlusal surface. Molnar (1971a), for example, defined a series of descriptive criteria for the assessment of the direction and form of the occlusal surfaces of worn teeth. To quantify the direction of the occlusal surface Koyoumdjisky (1956), working with unworn teeth, orientated skulls with the Frankfort plane horizontal, and measured heights of cusps at 1 mm intervals, obtaining angular measurements from plots of the data.

The problem is simpler when worn teeth are considered and the occlusal surface approximates a plane. Murphy (1964a) considered the vertical difference between the palatal and buccal surfaces of maxillary teeth to indicate the direction of the occlusal surface.
Butler (1972), Hall (1976) and Brown et al. (1977) measured the direction of the occlusal surface. Both Butler and Hall considered a line tangent to the most prominent points on the tooth being measured and the corresponding tooth on the opposite side of the arch as their reference line. Brown et al. adopted a similar approach, but related the direction of the occlusal surface to the mandibular plane rather than to the occlusal plane.

Butler noted that difficulties could arise in measuring the direction of occlusal surfaces because of the complex nature of the occlusal plane. Small variations in the antero-posterior plane in which the measurements were made could result in large differences in the recorded values due to the continually changing direction of the occlusal plane. This necessitates precise definition of the plane in which measurements are to be taken. Figure 24 summarizes the various methods by which occlusal surface orientation has been assessed.

Methods

The same criteria and reference points described by both Butler and Hall were used to assess the direction of the occlusal surface of the mandibular molar teeth. Rather than use a protractor to record directly from the skull, contours were recorded using a profile gauge in a similar manner to that described by Klami and Horowitz (1979) in their investigation of palatal asymmetry, and the orientation of the occlusal surface was measured from tracings of these contours (Figure 25).
Occlusal surface directions were recorded from the mandible only, with the profile gauge placed so that measurements were recorded in the same plane as that in which the arch breadths were measured. When one of a pair of teeth was missing, the gauge was aligned on the central fossa area of the measured tooth and the mesial or distal marginal ridge of the nearest tooth to that which was missing on the opposite side of the arch. Negative scores were assigned to ad lingum wear and positive scores to ad palatum wear. Experience suggested that the errors introduced in this way were relatively small.

Measurement of the orientation of the occlusal surface of each tooth did not provide any information about the general form of the occlusal plane. Therefore, to provide an overall indication of the relative orientations of the molar teeth, the occlusal plane for both the right and left sides was independently described as:

1. Helicoidal - when the orientation of the occlusal surface changed progressively from toward the buccal on the mandibular first molar to toward the lingual on the third molar,

2. Ad Palatum - where the occlusal surfaces of all mandibular molars were directed toward the buccal,

3. Ad Lingum - in cases where the occlusal surfaces of all mandibular molars were directed toward the lingual,

4. Ad Planum - when the bucco-lingual orientation of the occlusal plane was flat, or

5. Other forms

Subjects were excluded from this part of the study if any of the mandibular molars from the side being considered were missing. When the measured direction of one tooth was zero degrees it was considered, for
the purposes of this classification, as tending toward the direction of
the adjacent tooth. For example, if the directions of the mandibular
first, second and third molars were 0 degrees, -8 degrees and -16
degrees respectively the subject was classified as ad lingum on the
basis of the scores for the second and third molars, whereas if the
scores had been 16 degrees, 8 degrees and 0 degrees the subject would
have been classified as ad palatum.

To determine the significance of the errors involved in measuring
occlusal surface directions by this method, 20 randomly selected
subjects were re-examined some 2 months later. The mean differences
between first and second measurements (mean of first - second
measurements) ranged from -0.78 to +1.08 degrees, which appeared
relatively small considering the rather simple method of measurement
(Table 23). None of the observed mean differences varied significantly
from zero. The standard deviation of the single measures appeared
relatively large, ranging from 1.40 to 2.63 but, because of the large
variation in occlusal surface directions, errors only contributed
between 5.8 and 10.4 percent of the total observed variance.

Results

Means and standard deviations summarising the distribution of
measurements of occlusal surface directions of the molar teeth are
presented in Table 24. Student's t-tests did not reveal any significant
differences between the means for males and females but conclusions were
difficult to draw without considering the distribution of age and
attrition scores for the population.
The mean differences between left and right sides (difference = score for right side - score for left side) tended to be negative in males and positive in females. However, the differences were small and did not differ significantly from zero for either sex, suggesting that on average the direction of the occlusal surface was relatively symmetrical (Table 25).

The intra-class correlations tended to be smaller in females than in males (Table 26) indicating that, especially in the case of the first molar, females showed greater differences between left and right sides than males. For both males and females the correlation coefficients were highest for the first molar and lowest for the third molar.

Correlations between occlusal surface directions for ipsilateral molar pairs were all positive and relatively high suggesting, as expected, a degree of coordination between occlusal surface directions (Table 27). Correlation coefficients tended to be higher for males than for females and higher on the left side in males and the right side in females. Murphy (1964a) found no significant correlation between the orientation of the first and third molars in his study of the occlusal plane in Australian Aboriginals, but for the Narrinyeri population the orientations of the occlusal surfaces of all molar teeth were significantly correlated. For males, the correlations between first and third molar scores were significantly greater than zero on both the left and right sides and were no smaller than the correlations between adjacent molars, suggesting a closer association between the orientation of the mesial and distal zones of the helicoidal plane than was suggested by Murphy. In only one case (M1-M3 in females) was the correlation coefficient not significantly different from zero (p>0.05).
Consideration of the occlusal plane as a whole rather than the orientation of each tooth individually revealed important information. Clearly, of the possible occlusal plane relationships, the helicoidal plane was the most frequently observed (Table 28). Of the other possible relationships, the ad lingum pattern was the most common in both males and females. The ad planum pattern was not observed because of the precise criteria applied in its definition. There was no significant difference in the distribution of occlusal plane morphology between males and females.

Thirty-eight of the 48 subjects (79.2 percent) for whom both left and right dental arches were intact showed the same occlusal plane pattern on both sides (Table 29). In 32 of these 38 symmetrical subjects (84.2 percent) the pattern was helicoidal bilaterally. All 10 asymmetric subjects showed a helicoidal plane on one side and either an ad palatum or ad lingum pattern on the other.

The importance of age and advancing attrition as determinants of the form of the occlusal plane was also evident (Table 30). The helicoidal pattern was most frequent in the intermediate age group and was by far the most frequently observed pattern in any age group. The ad lingum pattern tended to occur in younger subjects, with the frequency falling from 35 percent in the younger group to 3 percent in the older group, while the ad palatum pattern was not observed in the younger group but was most frequent in older subjects (22 percent).

The changing orientation of the occlusal plane with time was also clear from plots of the direction of the occlusal surface against age (Figure 26) or attrition (Figure 27). The relationship between age and
the direction of the occlusal surface was clearly exponential but a relatively strong, linear relationship between attrition and occlusal surface direction was evident (Table 31). Correlations ranged from 0.46 to 0.84, tending to be higher in males than females, and were generally higher on the right side than on the left. No significant sex or left-right differences were evident.

The significant positive correlations between attrition and the directions of the occlusal surfaces suggested a different pattern from that described by Murphy (1964a) and Hall (1976) who both found that the direction of the occlusal surface in the third molar area did not change with attrition. It confirmed, however, Butler's (1972) contention that the orientation of the occlusal surface of all teeth changes with advancing attrition. Previous investigators may have concluded that the direction of the occlusal surface in the third molar area did not change with advancing attrition if they considered only young subjects or populations not showing very rapid attrition. Even in the Narrinyeri population, where attrition was relatively rapid, only the very oldest subjects showed mandibular third molars with a buccal orientation.

Nevertheless, determinants other than attrition also influence the direction of the occlusal surfaces. For males, positive correlations between arch breadth differences and wear directions were found for all molars (Table 32). Correlations were highest for the first molars, where arch breadth differences were greatest, and smallest for the third molars, where differences in arch breadth were relatively small or even negative. This supported Campbell's (1925) contention that the direction of the occlusal surface was related to differences in arch breadth. For females, however, the correlations did not conform to any pattern. There were a number of reasons why this might have occurred. Perhaps the most
likely explanation was the complications introduced by the significant negative correlations between arch breadth differences and attrition, which were evident in females (see Chapter 7).

Discussion

Both the qualitative and quantitative assessments of occlusal plane orientation confirm previous reports that a helicoidal occlusal plane is frequently observed in populations showing extensive dental attrition. While few previous reports describe the incidence of the helicoidal plane, the patterns of the means of measurements of molar occlusal surface directions for the Narrinyeri population are very similar to those reported for other non-Industrial populations (Table 32).

Of the 48 subjects for whom comparisons could be made, 32 (66.7 percent) showed a helicoidal pattern bilaterally. Of those who showed other patterns, the tendency was for an ad palatum occlusal plane in older subjects and for an ad lingum plane in younger subjects.

While some individuals showed very marked differences between the orientation of the occlusal surfaces on the left and right sides, the mean differences were small with the largest (1.7 degrees) being no greatest than the error involved in measuring the orientation of the occlusal surface.

The pattern of both left-right correlations and ipsilateral molar pair correlations was difficult to interpret. The only clear trends were for correlations to be higher for males than for females, and for left-right correlations to be highest for the first molar and lowest for
the third molar. This appeared to occur, in part at least, because partial eruption and unusual paths of eruption were more common in third molars than first.

The significant positive correlations between the orientations of the occlusal surfaces in the first and third molar areas for all but the left side in females, and between attrition and the direction of the occlusal surface for all molar teeth suggests that Murphy’s (1964a) contention that the direction of the occlusal surface of the third molar remained constant with advancing attrition did not apply to the Narrinyeri population. The scatterplot of the direction of the occlusal surface against attrition for third molars (see Figure 27) showed that for the Narrinyeri population the left mandibular third molar would not be expected to develop a buccal orientation until it reached an attrition score of 0.67, representing dentine exposure on 67 percent of the crown area. From the equation of the principal axis relating maxillary first molar and mandibular third molar attrition scores it can be shown that this corresponds to a score of 0.83 for the maxillary first molar. From the equation used to estimate ages, this represents an age of 73 years. Similarly, it can be shown that the mandibular right third molar would maintain its lingual orientation until age 65 years.

If the population studied showed less rapid attrition than was seen in the Narrinyeri population, or if only relatively young subjects were considered, it would be unlikely that any individuals showing a buccal inclination of the occlusal surface of the mandibular third molars would be seen. This may well explain why some investigators have concluded that the direction of the occlusal surface of the third molar does not change significantly with advancing attrition. In the Narrinyeri population the orientation of the occlusal surfaces of all molar teeth appeared to change with advancing attrition.
Physical anthropology is one of the oldest natural sciences and the earliest writings give evidence of particular interest in craniology. Hippocrates (460-357 B.C.) and Aristotle (384-322 B.C.) each described racial differences in cranial morphology and compared primate and human anatomy. In general, their discussions centered on very broad questions and their observations in anthropology served to emphasize their philosophy.

In later times da Vinci (1452-1519), Vesalius (1513-1564), Sigel (1578-1625), Tyson (1630-1708), Linneus (1707-1788), Blumenbach (1752-1840), Camper (1722-1789), Retzius (1796-1869) and many others made substantial contributions to craniology, introducing studies of proportions, volumes, dimensions and angles. Their work provided the basis for the systematic study of craniofacial morphology.

According to Penniman (1952:73), the publication of Darwin's "The Origin of Species" in 1860 marked the beginning of what he described as the "constructive" period of anthropology. Darwin's hypotheses provided a revolutionary framework for the systematic study of every aspect of anthropology, and during the later part of the 19th century and the early years of this century a considerable amount of information was collected and reported. Broca, Topinard and de Quatrefages in France, Virchow in Germany, Huxley, Duckworth and Turner in Britain and many others made substantial contributions during this period. The principal aim of these studies was the description and comparison of various racial groups.
Investigators working at this time were not without their critics, however. Macalister, in his presidential address to the British Association in 1892 (reported by Haddon, 1910:41-2), suggested that:

"Despite all the labour that has been bestowed on the subject, craniometric literature is at present as unsatisfactory as it is dull. Hitherto observations have been concentrated on cranial measurements as methods for the discrimination of the skulls of different races ... but there is underlying all these no justifying hypothesis; so that when we, in our sesquipedalian jargon, describe an Australian skull as microcephalic, phaenozygous, tapeino-dolichocephalic, prognathic, platyrhine, hypselopalatine, leptostaphyl ine, dolichuranic, chamaeprosopic, and microseme, we are no nearer to the formulation of any philosophic concept of the general principles which have led to the assumption of these characters by the cranium".

Soon after the discovery of Australia, interest was shown in the craniology of the Australian Aboriginal. According to Turner (1884), Sir Joseph Banks who travelled to Australia with Captain James Cook presented Blumenbach with two "New Holland" skulls which he described in publications which appeared at the end of the 18th century. Turner considered this to have excited so much attention that, by the time he prepared the report of the voyage of H.M.S. Challenger 80 years later, a very extensive literature was in existence. He described significant contributions by Gibson, Monro, de Quatrefages and Hamy, and Flower. Turner (1884) himself described 35 previously unreported Australian Aboriginal crania in the Challenger report and later described a further 18 specimens housed in the Anatomical Museum of the University of Edinburgh (Turner, 1891).
Duckworth (1904) reported "A critical study of the collection of Aboriginal Australian crania in the Cambridge University Museum" in which he tabulated measurements of the 38 specimens in the museum and summarised the findings of Davis, Flower, de Quatrefages and Hamy, and Turner. Similarly Morant (1927) pooled data from 18 previously reported studies to provide information on 300 specimens in his study of cranial variation in Australian Aboriginals.

Descriptions of the craniofacial morphology of the Australian Aboriginal have also been reported by Klaatsch (1908), Berry and Robertson (1914), Hrdlicka (1928), Jones (1929, 1931), Krogman (1932), Wagner (1937), Fenner (1939), Milecerowa (1955), Larnach and Freedman (1964), Freedman (1964), Brown (1965b, 1973), Larnach and Macintosh (1966, 1970, 1971), Yamaguchi (1967), Howells (1973), Margetts and Freedman (1977), Pietrusewsky (1979) and many others. The majority of these studies have been descriptive or have reported variation between Australian tribes or between Australians and other groups.

A number of the early investigations of cranial morphology in Australian Aboriginals provided a description of the general characters of the group. Prichard (1847:260) quoted William Dampier's report of contact with Aboriginals in the north-west of Australia in 1688 and 1699 as the first description of the group. Dampier described the Australian Aboriginals as:

"...the miserablest people in the world. They are tall, straight-bodied, and thin, with small long limbs. They have great heads, round foreheads and great brows."
Turner (1884), employing the jargon of his era, concluded that:

"... the general characters of the Australian skulls may be summarised as follows:—markedly dolichocephalic, tapeinocephalic, not strongly prognathic, as a rule platyrhine, microseme or mesoseme, dolichuranic and microcephalic."

This implied that the height and width of the skull tended to be small in relation to the length, that they were prognathic with a nose which was broad in relation to its height and an orbit height which was large in relation to its breadth. In addition, the palate tended to be relatively elongated and the cranial capacity relatively small.

Duckworth (1904) reached a similar conclusion. He suggested that the most striking features of the Australian Aboriginal were "...the long narrow skull, the very prognathous face, heavy brow ridges, and keeled cranial vault." More recently Montague (1960:440) described the general characteristics of the Australian Aboriginals as "primitive" citing the "...relatively large size of the palate and teeth, the fairly pronounced brow-ridges, small cranial capacity, sloping forehead and receding chin" as evidence of this. He recognised, however, that there was considerable regional variation in morphology.

The presence of variation in morphology between Australian tribes was recognised by the people themselves (Tindale, 1974:92-3) and has been appreciated for some time. Prichard (1847:263), after reviewing the reports of many of the first explorers, concluded that:
"... their accounts agree in all the principal points. The only material differences noted were in the bulk and stature which in the northern parts ... are much greater than in barren deserts."

He attributed this to the better supply of food in northern areas.

Turner (1884) quoted de Quatrefages and Hamy's division of Australian crania into coastal and inland groups, but he concluded that the evidence did not:

"...sustain the view that two or more distinct races of Aborigines ... have been or are now living side by side. In no series of crania from one locality do we find such a combination of characters so marked as to differentiate these from the natives of another locality."

Similarly, on evidence obtained from coefficients of racial likeness, Morant (1927) concluded that the subjects from different regions were sufficiently alike to be classified in a single group, with the exception of those from the north coast which he found differed in cranial vault size and shape, but were similar in general facial morphology.

When Brown (1973) compared subjects from the north of Australia with those from other areas, he also found differences in the cranial vault, but a general similarity in the dimensions of the facial skeleton. Describing subjects from the north of Australia as Group A and subjects from the south as Group B, he concluded that in the facial skeleton:
"Nasal breadth was slightly greater and nasal depth shorter in Group A skulls, and the palate was shorter and its vault higher than in Group B. The finding that morphological face height was shorter in Group A was associated with group differences in the inclinations of the nasal floor and mandibular base. The only group difference found in the lower face was for the variable ramus height which was slightly greater in the northern skulls."

The discussion of morphological variation in Australia has polarized over the years, and two diametrically opposed hypotheses have been offered to explain the observed variation. The first considers that the Australian Aboriginals represent a homogeneous population and that any of the observed variation which could not be explained in terms of adaptation to regional differences in environment, mutation, genetic drift or selection was within the normal variation expected within a population. This view has been traced back to Curr (1886-7) and is supported by Campbell, Gray and Hackett (1936), Howells and Warner (1937), Macintosh (1952, 1963, 1965), Abble (1968) and others.

According to the second hypothesis, the Australian Aboriginal represents a hybrid of various groups which migrated to Australia many years ago. The most recent form of this hypothesis has been described as Birdsell's "Trihybrid Theory". It was proposed by Tindale and Birdsell (1941) and has been supported by Hooton (1946), Gates (1960), Montague (1960:442) and many others. Kellock and Parsons (1970) summarised Birdsell's views in the following way:

... the primitive inhabitant of Asia before the third interglacial period was an unspecialized Caucasoid; from this element, differentiation into two more groups, the Negritos and Carpentarians, occurred in India and South-East Asia. During the Fourth Glacial Period, representatives of each of these three racial elements migrated to Australia... The so called Barrineans in the rain forest of North Queensland are believed to be related to the extinct Tasmanians and to have
descended from the Negritos, the first of the ethnic groups of Asia to enter Australia. The second group to migrate to Australia, the Archaic Caucasoid is considered to be the direct ancestor of the Murrayans of South-East Australia. The Carpentarians are the last group to have migrated; they are considered to be retained in their purest form in the north and north-west of Australia.

Resolution of the conflict between these two explanations is difficult for two reasons. Firstly, because isolated, living populations are required for biochemical studies of genetic markers, such studies have been limited to the north of Australia (eg. Kirk, 1966; Simmons and Graydon, 1971; Balakrishnan, Shanghvi and Kirk, 1975, Lie-Injo, 1976; Omoto and Misawa, 1976). Only skeletal material is available for Aboriginal tribes from southern Australia and, since very few skeletal collections from northern Australia are available, comparison of northern and southern groups is difficult.

Secondly, the debate revolves around what is, in a sense, little more than a difference in definition. Both hypotheses accept that the variation exists and while one group chooses to emphasise the similarities between people from various regions, the other group concentrates on the differences and explains these in terms of the pattern of migration of people into Australia.

Within the last few years considerable attention has been focussed on Australia as a key region in the tracing of early human migrations. This interest has followed the discovery of a number of archaeological sites which have yielded a rich and varied collection of early skeletal material. It is beyond the scope of this report to review recent research in this field but the cranial material from, for example, Kow Swamp and Lake Mungo (Thorne, 1976), Broadbeach (Wood, 1968), Roonka
(Pretty, 1977; Prokopec, 1979) and Coobool Creek (Brown, 1982), is likely to illuminate the debate on regional variation within Australia and affinities between early Australian man and man in South East Asia.

In addition to descriptive studies and investigations of interpopulation differences in cranial morphology, an increasing number of studies of the various determinants and correlates of craniofacial morphology have been reported in the anthropological, anatomical and clinical literature. For example, considerable interest has been shown in the relationship between climate and skull morphology. Davies (1932), Coon, Garn and Birdsell (1950), Froese and Burton (1957) and many others have described associations between cranial size and shape, and climate. For example, Beals (1972) found that cephalic index increased significantly as climatic conditions changed from dry-heat to wet-heat to wet-cold to dry-cold.

Thomson and Buxton (1923) related the nasal shape to the temperature of the air, suggesting that a larger surface area of nasal mucosa was required to warm the inspired air in subjects from colder climates. Similarly Weiner (1954) showed a relationship between absolute humidity and nasal index.

Guglielmino-Matessi, Gluckman and Cavalli-Sforza (1979) investigated differences between dendrograms based on anthropometric and biochemical data, and found that the two were more closely related when the variations in climate between the regions in which the populations they studied lived were eliminated. This implies that climate is an important factor in the determination of cranial morphology.
Other environmental factors have also been suggested as important determinants of craniofacial morphology. Carlson (1976), for example, found that over a 5000 year period from 3400 B.C. the cranial vaults of Egyptians increased in height and length, and the face became more inferiorly and posteriorly located. He attributed these changes to the transition from a hunter-gatherer to an agricultural subsistence.

The close relationship between cranial morphology and function has also been described by Hylander (1975), who suggested that some morphological features of the Eskimo were related to the functional demands placed on the masticatory system. He concluded that the broad face and the relatively anterior position of the zygomatic process of the maxilla, which produced the very flat faced appearance in Eskimos, together with the broad mandibular ramus, was evidence of a powerful, more anteriorly positioned masseter muscle. This, combined with a more vertical direction of the temporalis muscle, provided an improved mechanical efficiency in the masticatory system. Hylander suggested that the Eskimo skull was well adapted to resist the relatively large, vertical forces generated. For example, the long axes of the teeth were more vertical than in other populations, bony tori were relatively common, the mandible and the vertical facial dimensions were large and the cranial vault showed sagittal keeling, all of which contributed in some way to the resistance of vertical forces.

Evidence of an association between muscle activity and facial morphology has also been reported. Möller (1966), in his study of the electromyography of the masticatory and facial muscles, found significant associations between facial variables and muscle activity.
He noted, for example, that larger cranial base curvatures and more marked facial prognathism were seen in subjects with high masseter and temporals activity. Similarly, Ingervall and Thilander (1974) have shown that:

"The clearest correlations between muscle activity and facial morphology were found during chewing and maximal bite. During these functions the amplitudes in the temporal and masseter muscles were large in cases with a tendency to parallelism between the jaws bases and between the mandibular occlusal line and the mandibular line. These cases with considerable muscle activity are characterised by a rectangular shape of the face in profile and a small lower face height."

Ingervall and Helkimo (1978) also found that male subjects who exerted large bite forces differed from those who exerted small forces:

"...in having an anterior inclination of the mandible with a smaller anterior and greater posterior face height, a smaller gonial angle, a straighter cranial base and greater depth of the upper face, a tendency to parallelism between the mandibular occlusal line and the mandibular border as well as a broader maxilla."

It is difficult, however, to determine whether different muscle activity during the growth period produced the observed differences in morphology, or whether the muscle pattern reflects the structural framework. The functional matrix theory of Moss (1971) suggests that the first explanation is most likely but, whatever the explanation, these studies demonstrate the close relationship between form and function.
For many years, studies of the correlations between various cranial and facial variables have generally aimed to investigate the relationship between the various components of the cranial facial skeleton. Pearson (1896) reported correlations between skull length and width, and soon after studies by Macdonell (1901), Lee (1901) and Fawcett (1902) appeared. Since then a large number of similar studies have been reported.

In recent times, multivariate analyses of various types have been applied to describe the complex relationship between craniofacial variables (for example Howells, 1951, 1953, 1957, 1973; Schwidetzky; 1959, Landauer, 1962; Brown, Barrett and Darroch, 1965a,b; Solow, 1966; Brown, 1973; Liebgott, 1977; Cleall, BeGole and Chebib, 1979).

In addition to the relationship between various cranial variables, there is also evidence of the importance of extra-cranial factors as determinants of craniofacial morphology. Solow and Tallgren (1976), for example, found that:

"... the position of the head in relation to the cervical column showed the largest set of correlations with craniofacial morphology. Extension of the head in relation to the cervical column was found in connection with large anterior and small posterior face heights, small antero-posterior craniofacial dimensions, large inclination of the mandible to the anterior cranial base and to the nasal plane, facial retrognathism and a large cranial base angle and a small nasopharyngeal space."

Although many early investigators did not separate data for males and females, more recent studies have described significant sex differences in craniofacial morphology. Brown (1965b), in his study of the craniofacial morphology of the Wanbri tribe from central Australia,
found that "the facial skeletal profiles of male and female Australian Aborigines were similar in shape, but male linear variables were larger". In addition, he found that females showed a greater maxillary alveolar prognathism than males. Similar observations have been reported in a Chinese population by Wei (1969), in Danes by Ingerslev and Solow (1975) and in British by Bibby (1979).

Age changes in the craniofacial morphology of adults have not been extensively studied. Subjects over the age of about 18 years have usually been regarded as adult and the subsequent, small cranial and facial changes have been ignored. Lasker (1953), Israel (1973) and others have warned, however, that the age factor should be considered in studies of craniofacial morphology.

A number of investigators have found consistent age changes in facial dimensions in adults. Pfitzner (1899), for example, provided evidence that facial dimensions increased at least until 50 years of age. Similarly, Goldstein (1943) found that face breadths were greater in males over 60 years than in young adult males, but that face heights generally decreased with age due mainly to the loss of teeth. Coon (1950), however, found that face height increased with age, and similarly Tallgren (1957) and Thompson and Kendrick (1965) have reported consistent increases in anterior face height in short term longitudinal studies.

Hrdlička (1936), Campbell et al. (1936), Goldstein (1943) and Lasker (1953) have demonstrated age-related changes in various body dimensions in adults. Lasker, in comparing the results of his study of Mexicans from Paracho with data obtained from various areas of Mexico by Goldstein, concluded that:
"In head length there is little tendency to differ with age except for an increase with age in females. In head breadth and head height there is a significant increase with age in ...(the)... female series and also a tendency to increase ... in the males. The facial widths (zygomatic diameter and bigonial diameter) manifest an increase with age or a steady tendency in that direction in both sexes and for both sets of observations. In a number of measurements (stature, sitting height, biacromial diameter, chest width, total arm length, radius length, hand length and breadth, tibia length, foot length, total and upper facial height and nose height) the trend is for older females from Paracho to be larger and older males to be smaller."

Campbell et al. (1936), in a study of various central Australian tribes, found that zygomatic breadth, nasal breadth and length and ear length increased with age in both adult males and females. Mouth breadth, maximum interorbital breadth, nose length and nose height increased in males, and head breadth and various pelvic, abdominal and lower limb dimensions increased in females only. On average, morphologic face height remained constant with age in both males and females.

Ruff (1980) found similar changes in prehistoric American Indians. He described significant age-related increases in cranial height, cranial length, cranial base length, zygomatic breadth and bigonial breadth.

Lewin and Hedegård (1971) have reported results from a relatively extensive, longitudinal study of craniofacial dimensions in Skolt Lapps. They found that head length, head breadth, zygomatic breadth, bigonial breadth and morphologic face height had all increased, on average, during the 34 years between examination of subjects. They concluded that:
"The measurements of the face as well as those of the neurocranium showed that there is an increase in skeletal dimensions after the cessation of growth well up into the senium. This is due to the constant remodelling of the skeleton, either generally or in the origins and attachments of muscles. The increase amounts to almost 3 mm for the measurements of the neuro-cranium and close to 5 mm in the face. It is more frequent in the face skeleton, something which may possibly ...(be)... connected with the function of the jaws."

Age changes in craniofacial morphology in adults, although small, were clearly an important consideration.

Methods

In this study, the cranial and facial morphology of subjects was assessed by measurements recorded directly from skulls, and indirectly from standardized radiographs. Both methods are widely accepted and have been used extensively in various types of study. The reference points and variables considered in this study are defined in Appendix 5.

The radiographic reference points and methods follow closely those defined by Björk (1960) except where otherwise stated. Measurements were obtained from two series of cephalometric radiographs; the first were selected from those described by Brown (1973) in his study of the morphology of the Australian skull which included twenty of the subjects considered in this study. A similar procedure to that described by Brown was employed to obtain both lateral and antero-posterior cephalometric radiographs of the remainder of the present sample. To obtain this second series of radiographs, the skulls were orientated
using a Lumex cephalometer which resulted in a calculated enlargement of 5.6 percent for linear dimensions situated in the mid-sagittal plane of lateral films and the transporionic plane of the postero-anterior films. This compared with an image enlargement of 8.3 percent in the series described by Brown. Appropriate compensation for radiographic enlargement was made for all linear dimensions. Films were exposed at 68 Kvp and 11 Mas for most subjects, but at times exposures were varied slightly depending on the density of bone. Kodak X-Omat RP film was used with Dupont Cronex Hi-plus screens; processing was according to the manufacturer's recommendations.

Tracings of the radiographs were made on acetate drafting film. In the case of bilateral structures, where the images of the left and right sides did not coincide, the midpoint of the two images was taken as the reference point. Cartesian co-ordinates of each point were recorded from the tracings using a Hewlett Packard 9874A digitizer interfaced with a 9815A controller.

Distances and angles between selected reference points were calculated from the co-ordinates by the programme XYSCORE, a modified version of the COORD programme described by Barrett, Brown and McNulty (1968), using the CYBER 173 computer at The University of Adelaide.

In addition to the measurements recorded from radiographs, a number of dimensions were recorded directly on the skulls using standard anthropometric instruments. Landmark definitions described by Wilder (1920:37-76), Stewart (1957:135-159), Martin (1957:273-661) and Montague (1960:594-618) were adopted and are described in Appendix 5.
To assess the significance of the errors involved in both the radiographic and craniometric methods of measurement, a series of 20 subjects were reassessed some months later. The mean difference between first and second measurements (mean of first - second), the standard error of the difference, the standard error of a single measure and the percentage of the total observed variance attributable to measurement errors for each of the craniofacial variables are shown in Table 34. In general, the errors involved were small, but in a number of instances they were statistically significant.

Relatively large mean differences in endocranial length and breadth and in maximum frontal thickness were evident. In each case a degree of judgment was involved in assessing where the maximum dimension was to be measured. For all three variables, second measurements tended to be smaller than those recorded on the first occasion. Differences in endocranial height were smaller, however, perhaps a reflection of the more precise definition of the landmarks involved. Significant differences were also evident in the measurement of anterior cranial base length, cranial base angle, upper face height, palate height, pharyngeal depth, maximum ramus breadth and occlusal plane angle, although in each case the mean difference was less than 1 mm or one degree. These differences probably reflect the difficulties involved in reproducibly locating many of the reference points involved.

For some variables, measurement errors contributed a considerable proportion of the observed variance, casting doubt on the reliability of the measurements recorded. In the cases of foramen angle, minimum frontal thickness, pharyngeal depth and mandibular body thickness, errors explained between 23.4 percent and 46.4 percent of the total
observed variance. Conclusions based on these variables were therefore considered with caution. In general, however, the proportion of the variance attributable to errors was small. The tendency was for craniometric measurements to be more reliable than radiographic measurements, probably due to the direct method of measurement.

Few previous studies have assessed the significance of measurement errors in the way described here. Brown (1973) reported a similar type of analysis for selected variables. The errors he reported and those involved in this study were of similar magnitude. For example, the errors for the Narrinyeri group explained about 3.9 percent of the variation in total face height and about 10.2 percent of the variation in total mandibular length. In comparison, in Brown's study, errors explained 1.9 percent of the variation in total face height and 13.6 percent of the variation in total mandibular length. Similarly, in the case of pharyngeal depth, where errors were greater, they explained 46.4 percent of the observed variation in the Narrinyeri sample compared with 52.1 percent in the sample studied by Brown.

Results

Cranial vault

The means, standard deviations, minimum and maximum values and the percentage dimorphism (calculated as 100(male value-female value)/female value) for the various cranial vault dimensions are shown in Table 35. Sex differences in endocranial dimensions were generally small: male means were between 1.3 and 1.8 percent larger than female means, and none of the observed differences were significant at p<0.05 level.
External cranial dimensions were, however, significantly larger in males than in females. The smallest of these differences was for maximum cranial length, where the male mean exceeded the female mean by 3.6 percent. The largest difference was in maximum cranial breadth, where male and female means differed by 5.0 percent.

The largest of the sex differences was in maximum frontal thickness which reflects frontal sinus thickness as well as the thickness of the endo- and ectocranial plates of bone. Previous studies have shown the anteroposterior thickness of the frontal sinus to be significantly greater in males than in females (Brown, Pinkerton and Lambert, 1979). In addition, maximum frontal thickness is a measure of the degree of browridge development, a factor which has often been taken as an indicator of sex in studies of skeletal material. In the Narrinyeri population, the mean frontal thickness in males was 35.7 percent greater than the female mean.

Reports of cranial vault dimensions from studies of the Narrinyeri population by Hrdlička (1928) and Howells (1973) are presented in Table 36 together with cranial dimensions recorded in Western Australian Aboriginal crania by Margetts and Freedman (1977) and mean values for Aboriginal males from various areas of Australia reported by Brown (1973). The mean endocranial length and breadth in Narrinyeri males were considerably larger than those reported by Brown (1973). He noted, however, significant regional differences in both dimensions with subjects from the north showing smaller dimensions. In addition, endocranial heights in Narrinyeri subjects tended to be smaller than those reported by Brown, although regional differences were not evident in his study.
The external cranial vault dimensions reported in this study did not differ significantly from those reported in previous studies of the Narrinyeri population. Cranial lengths were larger, however, in Narrinyeri subjects than in either the Australian males described by Brown or the Western Australian group. Cranial heights, by comparison, tended to be smaller, especially in Narrinyeri females, although the differences were small. Mean values for maximum cranial breadths were similar in all groups.

The mean maximum cranial lengths for both male and female Narrinyeri subjects were clearly greater than those reported for other populations by Howells (1973), exceeding the mean for all groups combined by about 8 mm for males and about 7 mm for females (Table 37). Cranial height in the Narrinyeri population was only slightly smaller than the average reported for the other groups, while the mean maximum cranial breadth was 6.5 mm smaller in males and about 5.1 mm smaller in females than the overall mean.

The outstanding feature of the Narrinyeri cranial vault in comparison with both other Aboriginal populations and with non-Aboriginal populations, was its extreme length. In common with the other Australian Aboriginal groups considered here, the Narrinyeri showed a relatively small cranial breadth compared with the other populations considered by Howells.
Cranial Base

The distributions of linear and angular measures of the cranial base and of mastoid length and foramen angle are shown in Table 38. Both anterior and posterior cranial base lengths were significantly greater in males than in females. Total cranial base length was 3.2 percent larger in males than in females, but this difference was not significant. Cranial base angle and foramen angle showed only very small sex differences but mastoid length, which, like brow ridge development, is commonly used as an indicator of sex in crania, was 12.2 percent greater in males than in females.

Compared with previously reported data for Australian Aboriginals, a number of differences in cranial dimensions were evident (Table 39). The mean mastoid length reported in this study was 3 mm less than the mean for Western Australian males and was also considerably smaller than that reported in the Narrinyeri by Howells (Table 38). Rather than indicating important regional differences, this may well reflect differences in measurement technique between observers.

The mean posterior cranial base length in the Narrinyeri male sample was the same as that reported for Australian Aboriginal males by Brown (1973), but was considerably smaller than that reported in young adult male members of the Wallbri tribe from central Australia (Brown, 1965b). The mean posterior cranial base length in Narrinyeri males was 41.1 mm compared with 45.5 mm in Wallbri males. Similar smaller differences were observed in females, where the mean lengths for Narrinyeri and Wallbri subjects were 39.8 mm and 41.0 mm respectively. Considerable differences in cranial base angle between the two groups were also evident. The mean cranial base angle in the Narrinyeri exceeded...
that in Wailbri subjects by 6.0 degrees in males and 2.7 degrees for females. Brown (1973) reported similar regional differences in both posterior cranial base length and cranial base angle, with subjects from the north having a generally longer posterior cranial base and a smaller cranial base angle.

The same differences were evident when cranial base dimensions for the Narrinyeri were compared with data for modern Europeans (Ingerslev and Solow, 1975). Anterior cranial base lengths were similar in both groups (Table 40), but posterior cranial base lengths and the cranial base angle in Europeans were very similar to those reported for the Wailbri, with the mean posterior cranial base length exceeding that in the Narrinyeri population by 5.2 degrees in males and 2.9 mm in females. Similarly, the mean cranial base angle in Narrinyeri subjects exceeded that in modern Europeans by 5.1 degrees for males and 3.6 degrees for females.

Cranial base measurements for modern Chinese reported by Wei (1965) also differed in a number of ways from those recorded in the Narrinyeri population. Chinese males and females showed a smaller anterior cranial base length and a larger posterior cranial base length than Narrinyeri subjects. In addition, the mean cranial base angle was 6 degrees less in Chinese males and 2 degrees less in Chinese females, than in Narrinyeri subjects.

In comparison with other non-Aboriginal populations, the Narrinyeri showed a significantly larger cranial base angle and a shorter posterior cranial base. The differences between the groups in other cranial dimensions were small.
Nasal, Maxillary and Pharyngeal dimensions

Nasal and maxillary dimensions were generally significantly greater in males than in females (Table 41). Male values exceeded female values by from 3.8 percent in the case of palate length to 13.0 percent for palate height. Nasopharyngeal breadth was also significantly greater in males than in females, but none of the antero-posterior measurements spanning the nasopharyngeal region differed significantly between the sexes. Nasopharyngeal depth and intrapharyngeal depth were 0.4 and 1.1 percent larger in females than in males. These were the only two linear dimensions considered for which female values exceeded those in males.

Brown (1973) described significant regional variation in nasal breadths, which tended to be wider in the north of Australia than in other areas. The data for Western Australian AboriginaIs showed this same trend, with mean nasal breadth from Western Australia exceeding the Narrinyeri mean by 1.8 mm for males and 0.9 mm for females (Table 42). The values reported for Narrinyeri subjects by Howells (1973) were, however, of the same order in males and 0.5 mm larger in females than those reported in Western Australians so that from the available data the exact pattern is not clear. As with mastoid length, inter-observer differences in measurement methods may have been more significant than any regional differences in nasal breadth.

Mean values for bizygomatic breadth, maxillary breadth and external palate breadth in both male and female Narrinyeri subjects tended to be larger than those for Western Australians. For males, the values reported by Brown (1973) fell between the Narrinyeri and Western
Australian values, suggesting a degree of regional variation. In comparison with the facial breadths, the mean palate height was 2.2 mm greater in Western Australian males and 1.5 mm greater in Western Australian females than in Narrinyeri subjects.

Comparisons of the populations described by Howells (Table 37) suggest that the Narrinyeri were characterised by a large basion-prosthion length, a reflection perhaps of the marked prognathism evident in the group. The mean basion-prosthion length in the Narrinyeri exceeded that for all other groups except the Melanesians. Nasal breadths in Narrinyeri males were also relatively large, exceeding those reported for Europeans, Egyptians, Eskimos and South Americans, and were only slightly smaller on average than values for South African, Tasmanian and Siberian groups. The pattern for females was less clear.

The measures of facial breadths in males were generally larger in the Narrinyeri population than in the European, South African and South American populations described by Howells and in the Chinese described by Wei (1965) (Table 43). They were, however, smaller on average than North American and Siberian groups. In females, facial breadths in the Bantu group and the 6th to 8th century French described by Peyre (1979) were smaller than the Narrinyeri group, which in turn were smaller than the Eskimo and American Indian groups. For the Chinese females described by Wei, cranial breadths were of about the same magnitude as those seen in the Narrinyeri population.
Mandible

As with other linear dimensions, the dimensions of the mandible were generally larger in males than in females (Table 44). The smallest sex differences were in mandibular body thickness and mandibular ramus breadth, where the mean values for males exceeded female means by 2.1 and 3.1 percent respectively. Total mandibular length was significantly greater in males than in females. Other mandibular breadths, body and ramus dimensions were between 7.3 and 11.8 percent larger in males than in females. Gonial and symphysis angles were similar in males and females.

Compared with Western Australian Aboriginals, the Narrinyeri subjects showed generally greater bicondylar, bgonial and minimum ramus breadths (Table 45). In addition, the gonial angle was considerably smaller in Narrinyeri subjects than in either Wallbri or Western Australian Aboriginals. In contrast, symphysis angle was of about the same magnitude in both the Narrinyeri and Wallbri groups. The symphysis angle in the Narrinyeri population was, however, considerably greater than angles reported in either Modern Europeans or Chinese (Table 46). The mean symphysis angle in the Narrinyeri exceeded that in modern Europeans by 16.8 degrees for males and 14.6 degrees for females. The gonial angle in Narrinyeri subjects was considerably smaller than that in other groups. Modern Chinese and European values exceeded those for the Narrinyeri population by about 8 degrees in males and 6 degrees in females.
Compared with medieval French, minimum ramus heights in the Narrinyeri were relatively small with the mean for the French sample exceeding that for the Narrinyeri by 4.0 mm in males and 1.9 mm in females. However, ramus breadths were greater in the Narrinyeri where mean values exceeded those for the French group by 5.3 mm in males and 4.3 mm in females.

Facial prognathism and Facial planes

No significant sex differences were evident in any of the measures of facial prognathism (Table 47). The tendency was, however, for maxillary basal prognathism, and to an even greater extent maxillary alveolar prognathism, to be greater in females than in males, reflecting Brown's (1965b) observation of greater maxillary prognathism in Wallbri females. The inclinations of the maxillary base and the occlusal and mandibular planes were similar in males and females.

Measurements of facial prognathism were similar in each of the Aboriginal populations considered (Table 48). The only significant difference between Narrinyeri and Wallbri populations was in the mandibular plane orientation, which was considerably greater in Wallbri females than in Narrinyeri females.

Compared with modern European subjects, the Narrinyeri population showed greater maxillary and mandibular alveolar prognathism and greater maxillary basal prognathism, the means for each of these variables in the Narrinyeri population exceeding those for the other groups by

- 112 -
between 5.6 and 8.2 degrees (Table 49). Differences in mandibular basal
prognathism were less marked, however, with Narrinyeri means exceeding
those for modern Europeans by about 2.5 degrees and for Chinese by about
3.8 degrees.

Mandibular plane inclinations also varied between the populations
considered. The mandibular plane angle was about 3.3 degrees greater in
modern Europeans and about 8.0 degrees greater in modern Chinese than in
Narrinyeri subjects.

Anterior Face Heights

Means, standard deviations, maximum and minimum values and the
percent dimorphism for various measures of anterior face height are shown
in Table 50. Male values generally exceeded those for females by
between 2.3 percent (in the case of maxillary height) and 11.8 percent
(for mandibular height).

Because of the method employed in measuring face heights,
comparable data were generally not available. The upper face height in
the Narrinyeri population would appear to be similar to that described
in other Aboriginal populations but was clearly smaller than that
reported in modern Chinese and modern Europeans (Tables 48, 49). Total
face height in the Narrinyeri was similar to that reported in Australian
males by Brown (1973), but was smaller than that recorded in the Wallabi
population. In this case, the relatively young age of the Wallabi
sample and minimal occlusal attrition in the population may have
influenced this difference.

- 113 -
Age Changes

Correlations between age and the various craniofacial variables are shown in Table 51. In general, the correlations were weak, ranging from \(-0.56\) to \(+0.46\). A number of the significant correlations probably arose as a result of age-related effects such as dental attrition rather than as a result of age \(\textit{per se}\). For example, the observed decrease in the orientation of the occlusal and mandibular planes and the significant increase in mandibular prognathism with age were probably associated with a decrease in lower face height, especially in interalveolar height, which occurred as a result of advancing attrition, rather than age itself.

Similarly, the observed decreases in palate height and breadth with age were probably partly due to a reduction in alveolar bone height caused by periodontal disease, which was more severe in older subjects. In this instance, the more superior and medial location of the alveolar crest, which determined the point endomolare, resulted in relatively smaller palate heights and breadths. Mandibular body height also tended to decrease with age as the height of alveolar bone was reduced by periodontal bone loss.

In addition to the significant correlations which might have arisen by chance, particularly in females, a number appear to reflect sampling differences between various age groups. The significant negative correlations between age and endocranial length, basion-bregma length, mandibular body thickness and total mandibular length probably did not
reflect real differences, but were more likely the result of differences introduced in the selection of subjects, a problem which is inherent in all cross-sectional studies.

The significant positive correlations between age and bizygomatic and maxillary breadths in males probably reflect similar trends reported by Campbell et al. (1936), Goldstein (1943), Lasker (1953), Lewin and Hedegård (1971) and Ruff (1980), namely a continual surface deposition of bone during adult life.

Discussion

Sex differences in cranial and facial morphology were evident in most linear dimensions, reflecting the generally greater size of male subjects. Dimorphism was particularly marked for those variables used as indicators of sex, namely maximum frontal thickness and mastoid length.

The tendency was for sex differences in endocranial dimensions to be relatively small (less than 2 percent), while differences in the various mandibular dimensions were considerably greater. Variables commonly taken as indicators of muscularity and large masticatory forces, such as bizygomatic breadth, ramus height and symphysis height, were 11 to 12 percent larger in males than in females, reflecting the greater muscularity of male subjects. Differences in maxillary and nasal dimensions were clearly greater than those in endocranial dimensions, but were smaller than those in the mandible. Only antero-posterior dimensions of the nasopharynx were larger in females than in males, an important factor, perhaps, in the slightly greater maxillary prognathism which was evident in females, despite their smaller palate length.
Where comparisons were possible, the data obtained in this study showed the same general pattern described in previous investigations of the craniofacial morphology of the Narrinyeri population (Hrdlicka, 1928; Howells, 1973). The only large differences were in mastoid length in males and nasal breadths in females, where the population means reported by Howells exceeded those for the sample considered in this study. This may reflect differences in measurement technique or be an indication of sampling differences between the studies.

The Narrinyeri population differed in a number of ways from the Aboriginals from Central and Western Australia. In general, the differences were in variables reflecting muscularity. The Narrinyeri subjects showed relatively large facial breadths, a large ramus breadth and a smaller gonial angle than subjects from either Central or Western Australia. These are variables which have been shown in various electromyographic studies to be associated with relatively large muscle activities.

In addition, the Narrinyeri population showed a maximum cranial length which was large in relation to the other Australian groups and non-Aboriginal populations in general. Cranial breadth, in comparison, was greater in other groups than in the Narrinyeri so that the dolicocephalic label applied by early craniologists accurately described the comparison between the Narrinyeri and both other Australian Aboriginal groups and non-Aboriginal populations.

The marked prognathism described in Australian Aboriginals by many previous investigators was also evident in the Narrinyeri population. Basion-prosthion length and the angular measures of maxillary and
mandibular prognathism were clearly greater in the Narrinyeri than in either the European or Chinese groups considered. The differences in mandibular basal prognathism were smaller, however, than those for maxillary basal and alveolar prognathism and for mandibular alveolar prognathism, a tendency also displayed by the symphysis angle which was greater in the Australian Aboriginal group than in other groups. This produced the "receding chin" described by Montague (1960:440).

The cranial base morphology in the Narrinyeri was different from that in either the other Australian populations or in the non-Aboriginal populations considered here. The cranial base angle was clearly greater, and the posterior cranial base smaller, than in the other groups, a tendency observed by Brown (1973). Whether this reflected differences in head balance, pharyngeal morphology or perhaps in the position of the sella point is not clear. Solow, Barrett and Brown (1982) have suggested that the relatively short posterior cranial base seen in Australian Aboriginals is associated with a general shortening of the cervical spine. In addition, the cranial base angle has been shown to be associated with higher activity in the masseter and temporalsis muscles by Möller (1966), although Ingervall and Helkimo (1978) have shown that greater masticatory forces were seen in subjects with relatively straighter cranial bases. The exact implications of these observations are not clear as yet, however.

The observed age changes in various cranial and facial dimensions were generally small, and in most cases could be explained in terms of changes related to the progressive reduction in anterior face height with advancing attrition. Increases in bizygomatic and maxillary breadths were evident in the male subjects and, as described by previous investigators, these changes appeared to be the result of continual bone
deposition with age. It is unlikely that other small, age-related changes would be detected in a cross-sectional study.
TEMPOROMANDIBULAR JOINT MORPHOLOGY

For many years the human temporomandibular joints have been the subject of extensive investigation and controversy. This has been stimulated by their unique evolution, embryogenesis, growth, morphology and the functional demands to which they are subjected as components of the masticatory system (Storey, 1979).

The questions of whether the joint is load-bearing during function and subject to remodelling have also been debated. Some authors have suggested that the mammalian temporomandibular joint is not load-bearing (eg. Wilson, 1920, 1921; Robinson, 1946; Scott, 1955; Steinhardt, 1958; Tattersall, 1973) while others believe that the joints are "fixed and immutable" (Cohen, 1956) and not subject to remodelling.

Mechanical analyses of the forces acting on the temporomandibular joint have indicated, however, that the joint is subjected to load under certain conditions (Barbenel, 1974; Heckneby, 1974). In addition, by implanting strain gauges immediately below the temporomandibular ligament of Macaques, Hylander (1979) measured the forces acting in the bone adjacent to the joints during mastication and isometric biting. He found that:

"The macaque TMJ is loaded by a compressive reaction force during the power stroke of mastication and incision of food, and during isometric molar and incisor biting. TMJ reaction forces are larger on the contralateral side during both mastication and isometric molar biting."
In addition he determined that:

"Patterns of ipsilateral TMJ reaction force ... during isometric biting vary markedly in response to the position of the bite point. During biting along the premolars or first two molars a compressive reaction force acts about the ipsilateral TMJ; however, when the bite point is positioned along the M3, the ipsilateral TMJ has either very little compressive stress, no stress or it is loaded in tension."

These observations suggest that when the bite point is anterior to the resultant vector of the forces elevating the mandible the joint acts as the fulcrum, whereas when the bite point is distal to the resultant vector the food bolus acts as the fulcrum and tensile forces are applied to the joint. Similarly, Brehnan et al. (1981) implanted a strain gauge into the articular surface of the condyle of a Macaque monkey. They detected loads of the order of 1-3 lb. during molar chewing and 3-4 lb. during incisal biting.

Although the pattern of joint remodelling should reflect the functional forces acting on the joint, the exact determinants of joint morphology are poorly understood. By the age of about 20 years, when growth of the mandibular condyle is virtually complete, the condylar surface is usually convex in every direction. Little is known, however, about either the morphology of the articular eminence at this age or the rate and pattern of remodelling in the temporomandibular joint. Moffett et al. (1964) concluded that:

"Articular remodelling must be viewed as the interplay between stimulus and response ... (but that) ... we know little more than that it exists to a remarkable degree in the TMJ."
If the temporomandibular joint is load bearing during function, evidence of remodelling would be expected. Ingervall, Carlsson and Thilander (1976) found that the joint responded by changes in the rate and direction of condylar growth until age about 20 years when condylar growth ceased. Recent experimental work by Petrovic and his colleagues has confirmed a relationship between altered function and the direction and amount of condylar growth in young animals. They have proposed a biofeedback mechanism to account for the relationship (Petrovic and Stutzmann, 1977).

Adams et al. (1972) demonstrated that when orthodontic forces which tended to retrace the maxilla and protrude the mandible were applied to the teeth of young monkeys, changes in the direction of growth of the condyle resulted. Applying the same forces to adult monkeys, however, produced areas of remodelling in the articular eminence and, in some cases, regions of tissue destruction. Similarly, Moffett et al. (1964), Blackwood, (1966a,b) and Mongini (1972) each described the remodelling process in the adult temporomandibular joint. In addition, Mongini found that remodelling:

"...had a minority incidence ... in the youngest age group (18-22 years). In the other age groups, however, remodelling of some kind was a consistently common finding."

Moffett et al. (1964) described variations in the thickness of the articular surface tissue between different parts of the joint and, more recently, Griffin, Hawthorn and Harris (1974) observed an increased thickness of the articular tissue in areas of bone resorption. In addition, Hansson and Nordström (1977) found evidence that in adults:
This would suggest that in areas of regressive remodelling (Johnson, 1959, 1962) early changes in the bone, which would be evident radiographically and on examination of skeletal material, may not be detected in autopsy material where increases in the thickness of the articular tissue could maintain the original gross morphology. In this case the earliest signs of remodelling would be seen in the bone with soft tissue changes only appearing later. In comparison, cartilage proliferation in progressive remodelling would probably result in changes in the gross morphology of the joint which would not be accompanied, in the early stages, by parallel changes in the bone.

The variable relationship between the form of the articular surface tissue and the morphology of the underlying bone complicates the integration of information obtained from clinical radiographic studies and studies of skeletal material where the morphology of the bone is considered, with the results of autopsy investigations where the morphology of the articular tissue is considered. Consequently the findings of studies employing different methods need to be interpreted with caution.

In addition to the functional factors which must influence temporomandibular joint morphology, age and sex differences in the morphology of the joint have been described. Öberg et al. (1971), in a study of autopsy material, found that the incidence of joint remodelling increased with age. Similarly, Yale et al. (1966) described a tendency for the superior surface of the condyle to flatten with age. They also
found a slightly higher incidence of the convex superior condylar surface type in males and the flatter surface in females. Lindblom (1976) described both age and sex differences in joint morphology. He concluded that the temporal fossa was larger in males than in females and that the articular eminence tended to decrease in height after about 40 years of age. In Australian Aboriginals, Campbell (1925) found that fossa depth increased with age in adults, from an average of 4.5 mm in young adults to 5.6 mm in the oldest group.

Significant differences in the age-related changes in fossa depth between hunter-gatherers and agriculturists have also been described by Hinton (1981). He found that fossa depth increased with functional age (as judged by attrition scores) in hunter-gatherer groups, (Eskimo and Australian Aboriginal), with decreases occurring only in the oldest age groups. Demirjian (1963) also demonstrated significant differences in eminence height between various groups. Yale et al. (1966) did not detect any significant variation in the incidence of various condyle shapes between American Caucasoids and Negroes, however.

Sex differences in the medio-lateral dimensions of both the condyle (Wedel, Carlsson and Sagne, 1978) and the temporal fossa (Hinton and Carlson, 1979) have also been demonstrated. Significant differences in antero-posterior condyle dimensions (Porowski and Bruska, 1978) and articular eminence height (Demirjian, 1963) have also been observed.

Racial and temporal differences in temporomandibular joint morphology have also been documented. Duckworth (1904:470), for example, suggested that an extremely flattened and shallow glenoid fossa was characteristic of Australian Aboriginals while Knowles (1915)
suggested that the Eskimos were "the champions of the shallow fossa", a characteristic which he proposed was associated with the relatively well developed mandible and masticatory muscles.

Porowski and Bruska (1978), however, described consistent differences in condyle morphology between groups. They suggested that:

The mandibles of Australian skulls showed the elongated plane heads with sharp borders. The transverse dimension of the mandibular head markedly surpassed the sagittal one. The mandibles of the skulls from Milicz (Poland) showed the heads of elongated shape, plane surface and sharp borders, however, the difference between the transverse and sagittal dimension was less striking than that in the Australian skulls. In contrast, the skulls of individuals ... from Uganda showed almost sphaeric (sic) heads with rounded border. The transverse dimension was close to the sagittal one."

Temporal changes in joint size have also been described. Hinton and Carlson (1979) found that over a 10,000 year time period the size of the fossa decreased significantly, especially in males. They suggested that the observed changes were:

"... most likely the result of the reduction in masticatory muscle robusticity and resultant changes in craniofacial form ... (associated with) ... the transition from a hunting and gathering to an agricultural subsistence."

A number of investigators have reported significant asymmetry in temporomandibular joint morphology. Sullivan (1917) found "a marked asymmetry of the fossa" in each of the skeletal populations he examined and Lindblom (1976) reported that the left joints were significantly larger than the right in radiographs of normal subjects. Yale et al.
(1966) also found a low level of symmetry in both condyle dimension and orientation. They noted that the medio-lateral dimensions of right and left sides coincided in only 35.9 percent of subjects and that in only 26.0 percent did the horizontal and vertical angulations on left and right sides coincide.

In contrast, Weinberg (1978) suggested that the asymmetry in joint dimensions measured from radiographs was relatively small (less than 0.2 mm) and therefore of no great significance. Similarly Campbell (1925) found that asymmetry of the temporal fossa was rare in Australian Aboriginals, except in cases where pathological changes in the joint affected only one side. This raises the possibility that some of the studies reporting marked asymmetry in joint morphology may have included subjects with pathological changes.

Very few investigations of associations between joint parameters have been reported. Mongini (1975) noted that the orientation of the long axis of the condyle in the coronal plane determined whether the medial or lateral pole underwent remodelling. Lindblom (1976) found that condyle and fossa morphology were well correlated and Porowski and Bruska (1978) reported a number of relatively high correlations between indices of condyle form and eminence height. Nevertheless, little is known of the extent to which condyle size, shape and orientation and fossa morphology are related.

One of the problems commonly involved in studies of the temporomandibular joint has been the lack of satisfactory methods for assessing and classifying the morphology of the joint. Early studies relied on a classification of the fossa according to its depth (deep, medium, shallow or flat) and length (short or elongated) (for example
The antero-posterior and medio-lateral dimensions of the mandibular condyle provide an indication of the overall size of the joint (for example Öberg et al., 1971; Porowski and Bruska 1978), and some investigators have measured the horizontal and vertical orientation of the condyle (e.g. Yale et al., 1966; Bergman and Hansson, 1979). However, little is known of the determinants and functional correlates of condyle size and orientation.

A number of non-metric classifications of condyle morphology have also been described. In their study of human autopsy material, Öberg et al. (1971) described the superior surface of the condyle as, (1) rounded or slightly convex, (2) largely plane, (3) ridge shaped, or (4) other. In addition they described the outline of the condyle when viewed from above as, (1) oblong, (2) rounded, (3) tapering to the lateral, (4) tapering to the medial, or (5) other. Wedel et al. (1978) also adopted these descriptive criteria in their study of the temporomandibular joint morphology of Scandinavian skeletal material.

Yale et al. (1966) classified condyles according to the shape of their anterior, posterior and superior surfaces. The anterior and posterior surfaces were described as, (1) concave, (2) convex, or (3) plane, while the superior surface was classified as, (1) flat, (2) convex, (3) angled, or (4) rounded. This classification provided 36 possible morphological combinations. Of their series of 2959 condyles, 98.1 percent could be assigned to one of these 36 groups.

Mongini (1972), after consideration of a series of condyles, identified 8 morphological types. They were:
1. Rounded;
2. Flattened, overhanging medial and lateral poles;
3. Marked lateral slope with flaring and flattening;
4. Marked medial slope;
5. Downward flattening of both slopes and their merger in a single, extensive surface;
6. Thin condyle with backward flattening;
7. Triangular flaring of the lateral slope, and
8. More or less marked depression of the posterior wall.

These categories were not mutually exclusive however, as Types 6 and 8 referred to the posterior surface, while the other 6 groups described the morphology of the anterior and superior surfaces.

Interest has also been shown in the temporal fossa and articular eminence but only Öberg et al. (1971) defined criteria for the classification of their morphology. They described the inferior, medio-lateral outline of the articular eminence as, (1) slightly concave, (2) largely plane, (3) very convex, or (4) other shapes.

Recently Hinton and Carlson (1979) measured the distances between the postglenoid process, the articular tubercle and the "junction of the squamosal suture and tympanosquamosal fissure" and calculated the area of the triangle formed by these three points to describe joint morphology.

The height and slope of the articular eminence have been commonly taken as indicators of temporal fossa morphology. While the reference points for the measurement of eminence height are widely accepted
(Angel, 1948; Lindblom, 1976; Seward, 1976) there is little agreement about the method for measuring eminence slope. Angel (1948) considered the orientation of a line joining the maximum depth of the fossa with the most inferior point on the articular eminence relative to the Frankfort Horizontal Plane to indicate the slope and many investigators have adopted similar definitions (for example Granados, 1979).

Lindblom (1976) measured slopes from radiographs relative to a line joining the center of the external auditory meatus and the height of the articular eminence. He considered the angles between this reference line, the same line considered by Angel, and a line from the greatest depth of the fossa tangent to the slope of the eminence as indicators of eminence slope (see Figure 28). As an alternative, Seward (1976) applied a series of templates of known dimension to measure the diameter of the temporal fossa, suggesting that this reflected both the slope and height of the eminence.

Methods

For the purposes of the present investigation both metric and non-metric methods were used to describe the morphology of the temporomandibular joint. In order to facilitate comparisons with previously published reports, the criteria and reference points used conformed, where possible, to those most widely accepted.

Because this part of the study concentrated on the normal morphology of the temporomandibular joint, the specimens included were selected in the following way: when joint surfaces rather than total
joints were considered, subjects with no evidence of pathological change in any part of that joint surface were included. When joints as a whole were considered, only subjects without evidence of pathological change in any part of either joint surface were included.

Two condyle dimensions were measured directly from left and right condyles using dial callipers. The maximum medio-lateral diameter of the condyle was recorded parallel to its long axis, which was defined as the line connecting the most medial and most lateral extremities of the condyle. The maximum antero-posterior diameter was measured with the beaks of the callipers perpendicular to the long axis of the condyle.

To measure the orientation of the condyle in the frontal plane, the angle between the long axis and a reference line joining the lateral extremity of the left and right condyles when viewed posteriorly, was measured using a cephalometric protractor (designed by Dr A.T. Baum, Unitek Corporation). For uniformity, the protractor was placed with its body against the mandibular ramus (Figure 29a). Similarly the angulation of the condyle in the transverse plane was measured from the superior aspect using the same instrument and reference lines with the protractor placed parallel to the lower border of the mandible (Figure 29b).

These measurements were obtained in a similar manner to those described by Yale et al. (1966) and Bergman and Hanson (1979). Yale and his colleagues measured condyle orientation relative to a line connecting the posterior surfaces of right and left condyles for the transverse angle, and relative to the most superior points on the condyle for the frontal angle. This, like the method described and used here, suffers from an intrinsic bias introduced by recording relative to
part of the structure being measured. Bergman and Hanson (1979), who measured only the frontal angle, used the lower border of the mandible as a reference. While this has the advantage of being extra-condylar its stability over time and comparability between subjects is not beyond doubt.

In addition to these measurements, criteria for the description of condyle morphology were developed. Ackermann (1963) divided the temporomandibular joint into 3 functional areas: the posterior surface, the lateral part of the anterior surface and the medial part of the anterior surface, which he suggested were subjected to loading under different conditions and to varying extents. Ackermann suggested that the posterior condylar surface was loaded during mandibular movement to that same side, while the medial part of the anterior surface was loaded during movements to the opposite side and the lateral part of the anterior surface was loaded in protrusive movements of the mandible. Although this model might represent an over-simplification of the actual functional pattern of the joint (Mongini, 1975), it provides a convenient division for the condylar surface. Therefore, each of the three functional areas defined by Ackermann were considered independently and criteria for the description of the morphology of each surface were defined. The posterior surface was described as: (1) convex, (2) flattened, or (3) concave. Similarly the lateral part of the anterior surface was described as: (1) convex, (2) flattened, or (3) flared and the medial part of the anterior surface as, (1) convex, (2) flattened, or (3) very flattened.

To facilitate the identification of these changes and to clearly define the limits of each class, reference plates were constructed showing examples of each morphology. As these classes represented
divisions of what can be considered to be a continuous variable, the upper and lower limits of each class were also illustrated on the reference plates.

To describe the morphology of the temporal surface of the joint, the slope and height of the articular eminence were measured using a profile gauge (Figure 30). Because the fossa was complex in shape, the measurements recorded depended to a large extent on the technique employed and the way in which the reference points were defined.

The variable relationship between the long axis of the joint and the sagittal plane complicated the measurement of eminence slope. To provide some uniformity the profile gauge was placed in the line defined by the most superior point in the temporal fossa and the most superior point medio-laterally of the crest of the articular eminence. The projection of this line generally passed close to the lateral surface of the maxilla. This line would correspond approximately to the path followed by the most superior point on the surface of the mandibular condyle as it moved inferiorly and medially during movement of the mandible to the contralateral side. When orientating the profile gauge its body was held parallel to the Frankfort horizontal plane to ensure a standard orientation when profiles were traced, and to provide a reference line for measurements. The most superior point in the temporal fossa and the most inferior point on the articular eminence were marked on the tracings and the angle formed by a line connecting these points and the Frankfort horizontal plane was taken as the slope. The distance between the two points in a direction perpendicular to the Frankfort plane was taken as the height of the eminence.
To assess the significance of the errors involved in the measurement of temporomandibular joint morphology, a series of 20 subjects was reassessed some 3 months after they were first measured, and the two sets of measurements compared. The mean difference between these measurements (mean of first - second), the standard error of the difference, the standard error of a single measure and the percentage of the observed variance attributable to measurement errors for each variable are shown in Table 52.

The measurement of articular eminence height appeared to be relatively unreliable. In the case of the right joint, first and second measurements differed significantly (p<0.001), while in the case of the left articular eminence measurement errors contributed 38.1 percent of the total observed variance. For the other variables however, the mean difference between first and second measurements was not significantly different from zero (p>0.05), and errors only contributed between 3.5 and 16.6 percent of the total variance.

The morphology of each condyle was also reassessed 3 months after the first examination. The distribution of condyle morphology scores assigned on the first and second occasions are shown in Table 53. For all surfaces, identical scores were assigned on both occasions for more than 90 percent of the condyles examined, indicating a high level of agreement between first and second assessments.
Results

Mandibular Condyle

The distribution of medio-lateral and antero-posterior dimensions of condyles without evidence of degenerative change are shown in Table 54. In both cases, dimensions were significantly greater in males than in females. On average, the medio-lateral dimensions of the condyle in males were 1.5 mm greater on the right and 1.3 mm greater on the left than those of the females. On both the left and right sides the antero-posterior dimensions were 0.7 mm greater in males than in females.

The mean differences between left and right sides tended to be larger in males than in females, but for both sexes these differences were small and not significantly different from zero. Intra-class correlations between sides were smaller in males than in females (Table 55). This implied that the condyle dimensions tended to be more symmetrical in females. Correlations between age and condyle dimensions were generally positive, but none of the coefficients differed significantly from zero (Table 56).

The medio-lateral dimensions of the condyle were larger than those reported for non-Aboriginal populations and exceeded those reported previously for Australian Aboriginal populations. Antero-posterior dimensions were also relatively large, but were smaller than those reported for Polish subjects and for Australian Aboriginais from the River Murray basin (Table 57).
The distributions of condyle orientations in the joints with no evidence of degenerative changes are shown in Table 58. Differences in the means between males and females and between left and right sides were small and not significantly different from zero. The mean differences between sides were also small and intra-class correlations between sides tended to be lower in males than in females (Table 59). In general, comparisons of condyle orientations between sides and between sexes were similar to those for condyle dimensions. There was a tendency for a less symmetrical pattern in males than in females but none of the observed differences were significant (p>0.05).

Correlations between the transverse orientation of the condyle and age, for males and females, left and right sides were negative and generally weak, ranging from -0.19 to -0.31 (Table 60). Correlations between age and the orientation in the frontal plane were even weaker and showed no consistent pattern.

Comparisons of condyle orientations with previously reported data were complicated by differences in measurement methods. Where comparisons were possible, the condyle orientations in other populations were, in most cases, of the same order as those in the Narrinyeri population (Table 61). Results obtained in two previously reported studies of non-Aboriginal material differ from those described here, however. Bergmann and Hansson (1979) found a large number of subjects for whom the medial pole of the condyle was superior to the lateral pole (negative frontal orientation); while 52 (70 percent) of the 74 subjects they examined showed frontal condyle orientations between 5 degrees and 15 degrees, the medial pole was higher than the lateral pole in 19
percent of cases. Similarly, Yale et al. (1966) found that 329 (11 percent) of the 2947 condyles of Caucasoids and American Negroes which they examined showed negative frontal condyle orientations. In comparison, this was a rare finding in the Narrinyerl population where only 2 of the 88 normal condyles examined (2.3 percent) were of this type, suggesting that there may well be considerable inter-population differences in the frontal orientation of the condyle. Transverse condyle orientation in the Narrinyerl population did not appear to differ significantly from that reported for other groups.

The distribution of scores for posterior, anterior-lateral and anterior-medial condyle morphology for both left and right sides in males and females are shown in Table 62. Chi-square tests did not reveal any significant differences in the distributions between sides or between sexes. Therefore, the distribution with males and females and left and right sides combined is also included in Table 62. The posterior surface and anterior-medial surface of the condyle were convex in most cases, while the anterior-lateral surface showed signs of flattening in most subjects, with less than 20 percent of the condyles examined showing the convex morphology.

Table 63 shows the age distribution of condylar surface morphology with the data for males and females, left and right sides combined. The only clear trend was for the frequency of the convex shape to increase with age in the posterior and anterior-lateral regions and for the frequency of the flattened and flared types to decrease with age in these regions. It is difficult to interpret these results, however, as the exclusion of subjects with evidence of degenerative change in the joint, who in general tended to be older (see Chapter 11), biased the sample. Problems such as these are common in cross-sectional studies and are difficult to overcome.
The classification of each of the 3 joint surfaces on a 3 point scale provided 27 different condyle shapes: some were common but others were quite rare. Considering just the two anterior surfaces provided 9 possible morphological types (Table 64). Condyles with flattening of the anterior-lateral surface and a convex anterior-medial surface were very common, accounting for more than 50 percent of the specimens examined. Sixteen of the 104 condyles considered showed convex anterior-medial and anterior-lateral surfaces while a further 20 showed flattening of both medial and lateral surfaces. These three patterns accounted for 86.5 percent of all condyles.

Combining similar condylar types reproduced 5 of the 8 condyle types defined by Mongini (1975) (Figure 31). Because only the anterior surface of the condyle was considered, Mongini's Type 6 and 8 were excluded since they referred to the posterior surface. Mongini's Type 5 was seen in the material considered here but was excluded from the classification of condyle morphology because in every case condyles showing "downward flattening of both slopes and their merger into a single extensive surface" were associated with early degenerative changes in the temporoal fossa and were regarded as outside the normal range of condyle morphology (Figure 32).

The distribution of posterior condyle morphology in each of the five condyle types did not suggest any significant associations between the morphology of the anterior and posterior condylar surfaces. This was consistent with Ackermann's (1963) contention that the forces acting on the anterior and posterior surfaces arose in different ways and were independent (Table 65).
The majority of subjects (57.4 percent) showed the same condylar morphology on both left and right sides (Table 66). This symmetrical pattern was clearly more common in females than in males, with the left and right condyles showing the same morphology in 75.0 percent of females but in only 40.1 percent of males. With the exception of one subject, the differences between sides involved only one scoring unit in the extent of remodelling of only one joint surface. For example, if one condyle showed flattening of the lateral pole and a convex medial pole, the opposite condyle, if it did not show the same morphology, was either convex or flared at the lateral pole (a difference of one unit) and convex at the medial pole (no difference) or flattened on both the lateral pole (no difference) and also the medial pole (a difference of one unit). Subject A129 was the only exception, with the right condyle flattened on the lateral and convex on the medial, and the left condyle convex on the lateral and flattened on the medial.

Temporal Fossa and Articular Eminence

Assessment of the morphology of the temporal fossa was difficult because of its more complex shape. In the Narrinyeri population no significant differences in eminence slope between males and females or left and right sides were evident. Slopes ranged from 20 to 46 degrees, with means for both males and females of the order of 30 degrees (29.5 degrees to 30.9 degrees). Eminence heights tended to be slightly greater in males than in females, but no significant differences either between sexes or between sides were evident (Table 67).
The mean difference between left and right eminence slope (mean of right - left) tended to be greater in males (-1.94 degrees) than in females (0.38 degrees), although none of the observed differences were significant. Intra-class correlations between left and right eminence slopes and heights were significantly greater in females than in males, suggesting that even though the mean difference was small, there were greater differences between sides in males than in females. Neither side was consistently larger, however (Table 68). 

Correlations between age and both eminence slope and height (Table 69) tended to be negative (except on the left in males), but were small and not significantly different from zero.

The comparison of eminence slopes between populations was difficult because of the variation in reference points between studies. Eminence heights in the Narrinyeri population tended to be greater than those reported for Australian Aboriginals by Campbell, but smaller than in White Americans. They were of about the same magnitude, however, as heights reported for American Indians, West Africans and some other Australian Aboriginal populations (Table 70).

**Temporomandibular Joint**

Correlations between both linear and angular measures of joint morphology were generally weak (Table 71). Significant correlations between the antero-posterior and medio-lateral condyle dimensions were seen in both males and females (r= 0.22 to 0.49) suggesting a degree of coordination in overall condyle size. In addition, in females the antero-posterior diameter of the condyle showed a significant negative correlation with eminence slope and height (r= -0.39 to -0.62). Whether
this reflected the combined effect of remodelling on the condyle and eminence, which would tend to reduce the height of the eminence and increase the antero-posterior diameter of the condyle, or was the result of other developmental or functional factors was not clear.

The distribution of linear and angular measurements in each of the condyle types for which suitable sample sizes were available did not reveal any consistent differences in either joint size or orientation (Table 72).

Discussion

Based on previous reports of temporomandibular joint morphology in Australian Aboriginals, we would expect the Narrinyerl population to show symmetrical temporomandibular joints with a relatively flat temporal joint surface, an articular eminence which increased in height with age, and a large condyle in which the medio-lateral diameter clearly exceeded the antero-posterior diameter. Although the data generally confirmed these expectations, a number of points warrant further discussion.

Sex differences in linear dimensions of the temporomandibular joint (medio-lateral and antero-posterior condyle dimensions and eminence height) have been reported in a number of studies, and it has been suggested that these differences were greater in hunter-gatherer groups than in agriculturists. In the Narrinyerl population, eminence height tended to be greater in males than in females although the large measurement errors involved complicated interpretation of the
significance of the difference. Similarly, both antero-posterior and medio-lateral condyle dimensions were significantly greater in males than in females, confirming the trends observed in previous studies. However, no significant sex differences were evident in measures of joint shape (angular measures of condyle orientation and eminence slope) or in condyle morphology.

Conflicting evidence of age changes in temporomandibular joint morphology has been reported. Lindblom (1976) found that in a modern European population eminence height decreased with age, while both Hinton (1981) and Campbell (1925) have reported increases in eminence height with age in Australian Aboriginals. There was no evidence of age changes in condyle dimensions or in eminence height in the Narrinyeri population, although older subjects tended to show a higher frequency of convex condylar surfaces. This may well be an artifact of the method of sample selection.

Campbell (1925) suggested that the glenoid fossa morphology was relatively symmetrical but a number of other investigators have found a degree of asymmetry in temporomandibular joint morphology. Lindblom (1976), for example, found that the left joint was generally larger than the right. In the Narrinyeri population, the tendency was for correlations between left and right sides to be larger in females than in males, suggesting a higher degree of symmetry in females.

In addition to the age and sex differences in joint morphology which have been described here, the size and shape of the joint might be expected to reflect various anatomical and functional factors. Evidence of such associations will be described later.
Degenerative arthritis is a chronic, proliferative, non-inflammatory condition which results in progressive mutilation of joints. A distinction is usually made between primary and secondary forms of degenerative arthritis depending on whether or not a clearly definable aetiological factor is evident. Secondary degenerative arthritis may develop in joints already altered by other conditions. These include inflammatory conditions such as rheumatoid arthritis, metabolic disorders such as gout, structural abnormalities related to dislocations or fractures, and bone infarction. The pathogenesis of primary degenerative arthritis is still unclear, however. Two possible explanations of the development of degenerative arthritis have been proposed, one related to stress on the joint and the other involving changes in the joint cartilage.

Experimental studies have shown that mechanical stress alone is sufficient for degenerative changes to develop. McDevitt and Muir (1976) induced degenerative changes in the knee joint of mature dogs by sectioning the anterior cruciate ligament, rendering the joint unstable and so exposing it to abnormal stress. Radin et al. (1973) induced similar changes in rabbits by impact loading the joint at 60 cycles per minute for one hour per day for up to 36 days. They observed micro-fractures in the subchondral bone which, on healing, decreased the resilience of the bone and consequently exposed the cartilage to unfavourable stress.
Jurmain (1976), in an ethno-historical survey of four human skeletal populations, attributed degenerative changes in certain joints to particular customs of the group considered. He concluded that mechanical factors played a part in the aetiology of degenerative arthritis. Sokoloff (1972) also suggested that degenerative changes appeared in areas subjected to weight bearing and shear stress, but he clearly believed that the initial changes occurred in cartilage.

The concept of cartilage "softening" has been advanced recently by several investigators. It is most likely that this occurs as a result of a loss of proteoglycan from the cartilage matrix. This could be the result of increased destruction of proteoglycan by enzymes such as cathepsin D (Kempson et al., 1973), or decreased synthesis of proteoglycan due either to changes in the chondrocytes themselves, or to decreases in the number of chondrocytes during breakdown of the cartilage (Hjertquist and Lemperg, 1972). In addition, the possibility of mechanical stress acting either directly on the matrix to break down macromolecules or to affect the output of chondrocytes, has been suggested (Laurent, 1970).

Fassbender (1975) described the pathogenesis of degenerative arthritis in some detail. He suggested that the initial changes in primary degenerative arthritis might be influenced by genetic predisposition, mechanical factors affecting the joint, cartilage damage by lysosomal enzymes released as a result of trauma or inflammation, or subchondral bone necrosis which may interrupt the anchorage of cartilage to bone. Fassbender also described the pathogenesis of degenerative arthritis in joints with hyaline articular cartilage. He described initial small areas of superficial roughening which increased in size as a result of friction.
As the number and depth of the initially small cartilage fissures increased, the joint surface became fibrillated and flakes of cartilage detached. Further joint movement led to smoothing of these areas but in time further cartilage was lost. Although chondrocytes aggregated near the cartilage tears, it appeared that the formation of collagen and matrix was inadequate to repair these defects. The destruction and removal of the articular cartilage gave rise to a secondary synovitis which was usually accompanied by the formation of new subchondral bone. Eventually areas of complete cartilage erosion developed and the bone became sclerotic and eburnated. This bone, without the specially adapted properties of cartilage, was soon destroyed by the forces acting on the joint, and erosion through the subchondral bone into the marrow space occurred in many cases.

The destruction of cartilage is essentially a mechanically induced degeneration, leading to erosion of the subchondral bone and the eventual involvement of the marrow spaces, with the increased likelihood of a superimposed inflammatory response. The proliferation of tissue from the marrow spaces provides the possibility for repair of the affected joint surfaces, but in most joints this friable tissue becomes detached and is broken-down, adding to the effect of the earlier debris in irritating the synovium. Pseudocysts may develop in the marrow spaces as a result of the transmission of pressure from the joint cavity through defects in the subchondral plate. In addition, the synovial tissue may hypertrophy in the region of capsular attachment and subsequent ossification produces osteophytes in non pressure-bearing areas of the joint.
Epidemiological studies indicate a strong association between age and the incidence of degenerative arthritis. It is difficult to determine if the lesions are a direct result of the aging process or if they are the result of other age-related changes. Recently, Jurmain (1980) described important differences in the age-related incidence of degenerative changes in various joints. He suggested that local factors were more important in the development of degenerative changes in some joints (for example the elbow) than in others (for example the shoulder, hip, knee) and concluded that this was evidence of the multifactorial aetiology of degenerative joint lesions.

Because of the unique functional features of the temporomandibular joint and the differences between its fibrous articular tissue and the hyaline cartilage of other joints, the special pathology of the temporomandibular joint is important. Information derived from studies of other joints has been applied to the temporomandibular joint and investigations of the importance of both stress and, more recently, changes in cartilage have been reported.

The available evidence suggests that the temporomandibular joint is load-bearing and subject to remodelling. Bauer (1941), Lamont-Haver (1966), Mayne and Hatch (1966), Chalmers and Blair (1974), Kopp (1976) and many others have described degenerative changes in the temporomandibular joint and attributed them to the loads acting on the joints. In addition, many other investigations have revealed a relationship between degenerative joint change and dental changes, including partial and total tooth loss (Furstmann, 1966; Blackwood, 1969; Überg et al., 1971, Weisengren, 1975; Cran, 1976 and others). However, a number of investigators have failed to detect associations of this type (Ramfjord, Walden and Enlow, 1971; Toller, 1974).
Kopp (1976) reported an investigation of biochemical changes in the articular tissue of the temporomandibular joint. In hyaline cartilage, loss of glycosaminoglycans (chondroitin-6-sulphate, chondroitin-4-sulphate, keratan sulphate) is taken as an early indication of the development of degenerative arthritis (Mankin and Lipiello, 1971). Kopp found the highest concentrations of sulphated glycosaminoglycans, which are believed to increase the load-bearing capacity of the tissue, in the central area of the disc where chondroid cells were found. He also observed focal loss of sulphated glycosaminoglycans in areas of disc-thinning.

Blackwood (1963) found that the earliest degenerative lesions were seen in the "upper posterior articular surface" which would not normally be a load-bearing area. He recognised that the dentitions were adequate in only six percent of those he examined and, in addition, evidence of a "postnormal position of the condyle" presumably accompanied by loss of vertical dimension was frequently seen.

Toller (1974) suggested that the degenerative lesion observed in the temporomandibular joint differed in a number of ways from that seen in other joints. Clinically, the condition showed an earlier age of onset, a higher frequency in females than males, a lower frequency of osteophyte formation, an early spreading subarticular ossification, a rapid clinical course, and a tendency to repair. Toller also suggested that the age incidence, sex distribution, radiographic appearance (erosion with a low incidence of osteophytes) and the absence of any correlations with dental irregularities (in his series) all indicated a form of rheumatoid disease. The absence of clinical signs and symptoms...
of inflammation, the lack of raised erythrocyte sedimentation rate, the absence of serum rheumatoid factor, a generally monoarticular distribution, early loss of integrity of the articular surface with regressive changes in the bone, fibrosis rather than inflammation of the bone marrow and the presence of synovial hypertrophy, all suggested a degenerative component of the condition, however.

A number of radiographic and histological studies of clinical and autopsy material have also been reported. Bauer's (1941) survey of the temporomandibular joint revealed histological signs of degenerative arthritis in "almost all" of a sample of individuals ranging in age from 3 months to 81 years. Toller (1974) studied 150 cases of degenerative arthritis of the temporomandibular joint and found that the age of onset differed significantly from that seen in other joints. The occurrence was linearly related to age for most joints, whereas in the temporomandibular joint the incidence reached a peak at about 45 years and declined in older subjects. For other joints, degenerative changes were generally evenly distributed between sexes but Toller found that 85 percent of the subjects with degenerative arthritis of the temporomandibular joint were females. Similarly, Öberg et al. (1971) noted degenerative joint changes in 31 percent of females and 15 percent of males examined at autopsy.

At least 22 percent of the temporomandibular joints examined by Öberg and his colleagues showed signs of degenerative arthritis on gross examination; a further 55 percent showed changes classified as either arthritis or remodelling. In their series, the disc and temporal area showed the highest frequency of change. Of the arthritic joints examined, 78 percent of the discs and 72 percent of the temporal surfaces showed degenerative lesions, while only 6 percent of condyles
showed any change. Of all the degenerative lesions seen, 72 percent were situated in the lateral third of the joint in which case the disc was invariably perforated. The remaining 28 percent of the observed lesions were situated centrally, and in no case were changes in the medial third of the joint evident. In 69 percent of the joints in which the lateral third was affected, the adjacent part of the articular eminence showed signs of change. In addition, all of the arthritic joints showed extensive remodelling. The eminence commonly showed progressive remodelling on its posterior surface to give a plateau-like structure, while the condyle was flattened in the area of disc perforation.

Weisengreen (1975) studied discs from 198 human temporomandibular joints and found "a striking incidence of degenerative changes; notably bilateral". The incidence increased from zero in the fourth decade to between 35 and 40 percent in each of the later decades.

Degenerative changes have also been described in the temporomandibular joints of prehistoric Neanderthals (Brothwell, 1963) and in cranial collections representing precontemporary man In Australia (Brown, 1965a; Seward, 1976; Griffin et al., 1979; Richards and Brown, 1981), Egypt (Filce-leek, 1972), North America (Moffett, 1974), Sweden (Wedel et al., 1978), Europe (Griffin et al., 1979), and the Middle East (Alpagut, 1979).

The distribution of joint lesions in skeletal remains of Australian Aboriginals reported by Richards and Brown (1981) was similar to that described in autopsy material by Öberg et al. (1971). The temporal surface was affected more frequently than the condyle, the condition showed an early age of onset, the incidence was higher in older
subjects, and for the fossa at least, lesions tended to be situated more laterally. However, lesions were also seen in the medial areas of both condyle and fossa, and the incidence of degenerative changes was greater in males (43 percent) than females (33 percent). In addition, bilateral lesions were more common in the Australian Aboriginals (53 percent) than in modern populations where changes were usually unilateral (Toller, 1974).

In previous studies, a number of descriptive criteria for the classification of degenerative changes in the temporomandibular joint have been developed. In their study of human autopsy material, Öberg et al. (1971) described 3 categories of change in the temporomandibular joint: (1) local, marked irregularities of shape without evidence of lesions (arthrotic changes) of the articular surface; (2) local lesion on articular surfaces (arthrotic changes such as erosion, ruggedness); (3) extensive lesions of articular surfaces (arthrotic changes) and extensive changes in shape. They also noted the extent and location of lesions, describing areas of change as either (1) local (involving only the lateral, medial or central areas of the joint), or (2) extensive.

Recently, Hansson and Öberg (1977) adopted similar, but simpler descriptive criteria in their re-examination of the material originally studied by Öberg and his associates. They described "deviations in form and arthritis of the components" as either local when less than one third of the joint surface was involved, or extensive when more than one third of the joint surface showed evidence of degenerative change. Lesions were also classified as (1) shallow (with "lesions of the joint surface which was velvet-like to slightly scalloped in nature"), or (2) deep (with "lesions which resulted in a loss of substance in the soft tissue too, or in the region of the underlying hard structures").
Bergman and Hansson (1979) simply regarded "perforation and/or erosion of the surface layer" of any extent as evidence of degenerative change. As an alternative, Hansson et al. (1979) described these changes as: (1) a break in the continuity of the articular surface; (2) deterioration and abrasion of the articular soft tissue; (3) discolouration.

In their study of skeletal material, Wedel et al. (1978) classified surface changes of the bone as: (1) uneven surface with unbroken compact layer; (2) marked irregular surface or local proliferation of the compact bone layer; (3) compact layer broken up in areas of larger than 3 square millimeters or widely distributed small perforations.

In a previous study of degenerative arthritis of the temporomandibular joint in the Australian Aboriginals (Richards and Brown, 1981), changes in the bone were scored as:

- Grade 1. Localized erosive changes;
- Grade 2. Localized proliferative changes;
- Grade 3. Generalized proliferative changes;
- Grade 4. Eburnation of bone.

Each joint surface was divided into 3 regions antero-posteriorly (anterior, central and posterior third) and 3 regions medio-laterally (a lateral, central and medial third). Scores were assigned to each of these 9 sub-regions independently. Taking into account the distribution of scores for all regions, degenerative changes were classified as:
1. Minor changes (Grades 1 or 2) affecting one articular surface in any region;

2. Minor changes affecting both articular surfaces in any region;

3. Extensive changes (Grades 3 or 4) affecting one or both articular surfaces in up to 4 regions;

4. Extensive changes affecting one or both articular surfaces in 5 or more regions.

**Methods**

In the present investigation similar bone changes to those described previously (Richards and Brown, 1981) were identified (Figure 33), but a slightly modified classification was applied which suited the purpose of the study and simplified analysis. Based on the distribution of the observed changes, each joint surface was described as:

0. Normal;

1. Mildly affected - with changes of any Grade in less than half of the total area of the joint surface;

2. Severely affected - with changes in more than half of the total area of the joint surface.

To assess the reliability of scores assigned in this way, the temporomandibular joints of all subjects were reassessed 3 months after the initial examination. For the 146 temporal surfaces, identical scores were assigned on 142 occasions (97.3 percent). In 2 cases joints were assessed as normal on the first occasion and mildly affected on re-examination, and in a further 2 cases the temporal surface was
described as mildly affected on the first occasion and normal on the second. First and second assessments of the condyle agreed for all 147 surfaces considered.

Several subjects were excluded from this part of the study. In one case (subject A43) there was evidence of rheumatoid change in the temporal fossa (Figure 34), and in another (subject A37) a large accessory foramen was present on the inferior aspect of the articular eminence and the condyle was bifid in the region in which it would normally articulate with the part of the eminence in which the foramen was present (Figure 35).

Results

Previous investigators have reported a frequency of degenerative joint change of between 35 and 40 percent in pre-industrial skeletal populations. In the Narrinyeri people, degenerative changes were seen on at least one joint surface in 62.2 percent of males and 40.5 percent of females.

The distribution of joint change in left and right sides for the temporal fossa and for the mandibular condyle is shown in Table 73 with the data for males and females combined. Of the 31 subjects with changes in the temporal fossa, 20 (64.5 percent) showed changes in both fossae (Table 74), and in 11 (35.5 percent) only one temporal surface was affected. Similarly, 14 of the 21 subjects showing evidence of degenerative change in the condyle (66.7 percent) were affected bilaterally, while 7 subjects (33.3 percent) showed change in only one joint surface. In cases where only one joint surface was affected, the
tendency in both the fossa and the condyle was for these changes to occur on the left side. Considering condyle and fossa together, 18 subjects showed unilateral change, the left side being affected in 12 and the right in 6.

Sex differences in the frequency and severity of joint change are shown in Table 75. It is clear that males were affected more frequently than females and that the changes seen in males tended to be more severe than those in females. For both condyle and fossa, severe changes affected 20 percent of joint surfaces in males but less than 2 percent of surfaces in females.

The frequency of degenerative joint change was also clearly greater in older subjects (Table 76). Only 2 of the 26 temporal surfaces (7.7 percent) of subjects from the youngest group showed degenerative changes, and none showed any evidence of severe changes. No evidence of condylar changes was seen in the youngest age group, but in the oldest group 63.0 percent of temporal surfaces and 44.4 percent of condyles showed evidence of degenerative change, and in each instance the changes were severe in about 25 percent of subjects.

Consideration of the distribution of changes in the temporal and condylar surfaces of the same joint showed that changes were more common in the fossa than in the condyle. When only one joint surface was affected it was usually the temporal (Table 77). In addition, in all subjects where severe changes were evident, both condylar and temporal surfaces were severely affected.
Discussion

Comparative studies of joint pathology have been complicated by the difficulties inherent in relating autopsy and clinical findings (see Chapter 10). The available evidence suggests, however, that the changes seen in bone often occur earlier and are more advanced than those in the overlying articular tissue. Bean, Omnell and Öberg (1977) have shown that:

"... almost all arthrotic lesions in the soft tissue were associated with destruction of the subarticular compact bone ... (and that) ... in several joints, rather extensive destruction of the subarticular compact bone plate coincided with a macroscopically intact articular surface."

Under conditions of increased load, it seems that remodelling or destruction of the underlying bone may be associated with thickening of the articular tissue, so that macroscopic examination of the joint at autopsy might reveal a normal condyle even though there could be evidence of degenerative changes in the underlying bone. Direct examination of the bone appears to offer the advantage of detecting changes not evident on examination of the articular surface. A degree of care must be exercised, however, when comparing results obtained from studies of skeletal material with those of autopsy investigations.

The relatively high frequency of degenerative change in the temporomandibular joints of pre-industrial populations might be explained in a number of ways. Firstly, pre-industrial populations are represented by skeletal remains whereas most studies of modern groups have involved autopsy specimens, where the changes observed in the articular cartilage are likely to be less severe than those seen in the
underlying bone. In addition, it could be argued that the forces acting in the masticatory system in pre-industrial groups were greater than those acting in modern groups. Therefore, even if the methods of assessment were comparable, a lower frequency of joint change might be expected in modern populations.

The high incidence of arthritic change could also be secondary to inflammatory processes affecting the joint, rather than the result of functional factors. The most obvious inflammatory condition to consider is smallpox, which the available evidence suggests was pandemic among the Narrinyeri represented by the present material (see Chapter 2). There is no evidence, however, that smallpox results in any joint change. The virus that produces the skin lesion is blood-borne and so the relatively avascular articular tissue of the temporomandibular joint would probably not be affected (Burnett and Scherp, 1968).

The relatively high frequency of bilateral joint change in the Narrinyeri population compared with the predominantly unilateral distribution in clinical studies may again reflect diagnostic differences. It is conceivable, however, that the predominantly bilateral distribution in the Narrinyeri reflects the pattern of action of the various aetiological factors. If factors such as patterns of tooth contact and tooth loss are important in the development of degenerative changes, a generally symmetrical pattern of joint change might be expected in the Narrinyeri because Australian Aboriginal populations generally show symmetrical functional patterns (Beyron, 1964). In contrast, dental pathology and modifications to the functional pattern resulting from dental treatment are more likely to be unilateral in modern groups and, as a result, unilateral joint changes might also be expected.
The relatively high frequency of degenerative change in males in the Narrinyeri population might also reflect important functional differences between males and females, a possibility that is addressed as part of the study of the relationship between joint pathology and various functional and anatomical variables.
Section Four

CORRELATIVE STUDIES
In the absence of any adaptive or compensatory changes, progressive occlusal attrition would result in a marked reduction in lower face height. In some subjects, however, compensatory mechanisms act to maintain face height in the presence of relatively extensive attrition. Herzberg and Holic (1943), for example, found that anterior face heights in the American Indian skulls they examined did not decrease as attrition increased. This suggested that:

"... the position of the mandible is dependent upon the musculature and not on the occlusion of the teeth. The teeth evidently erupt into occlusion and into the intermaxillary space maintained by the musculature. The position of the mandible in any given individual remains constant by means of the balance afforded by the musculature and the teeth erupt throughout life space with the amount of attrition."

Sicher (1949:276), Begg (1954a,b,c), Sarnäs (1957), Murphy (1959c), Newman and Levers (1979) and many others have supported the concept of continual tooth eruption in man. Sicher summarized concepts of the time in the following way:

"... the active eruption of a tooth is, under ideal conditions and after facial growth has ceased, equal to the loss of substance on its occlusal surface; thus the face height is kept constant."

Thirty years later, Newman and Levers (1979), in a radiographic study of mandibles from an early Anglo-Saxon population, reached similar conclusions. They described:
"... continued tooth eruption through adult life compensating for reduction in the level of the occlusal plane due to attrition. No significant change occurred in clinical crown height, or in alveolar crest in relation to the inferior dental canal. There was a slight deposition of bone below the canal, probably at the lower border of the mandible. Rates of eruption and attrition were similar. There was a gradual diminution through life of the length of root enclosed in bone."

In addition to the continual eruption of teeth, it has been suggested that alveolar bone growth in adults might also partly compensate for the loss of crown height due to attrition. Murphy (1959c) found that in Australian Aboriginals both maxillary and mandibular heights were 0.4 mm to 0.6 mm greater in an advanced attrition group, aged about 50 years, than in a group aged about 30 years showing moderate attrition. Similarly Alnemo and Talari (1976) found that mandibular alveolar bone growth in contemporary Scandinavians occurred at a similar rate to that described by Murphy.

Not all investigators have found evidence of compensatory changes, however. Williams (1949) and Cran (1957) each proposed that continual eruption did not occur. Cran, in a study of Aboriginals from central Australia, concluded that:

"It is obvious that with these natives there is no physiological process of continuous eruption by which clinical height of the tooth crown is maintained during crown wear by attrition. Frequent instances can be observed both on skulls and living subjects of healthy teeth still functioning effectively although worn down almost to gum level."

A number of descriptions of the changes in face height with either age or advancing attrition have been reported. Monson (1921), Planer (1930), Mershon (1937, 1939), Tench (1938), Harris (1938), Thompson (1946, 1954), Kazlis (1948), Murphy (1959c) and others have described
reductions in face height with age or attrition in various populations. In contrast, Hrdlička (1936), Lasker (1953), Baer (1956), Tallgren (1957) and Thompson and Kendrick (1965) have described age-related increases in face height.

Whether face height increases, remains constant or decreases depends on the balance between the rate of attrition and the rate of compensatory tooth eruption and alveolar bone growth. The evidence provided by Tallgren (1957) and by Ainamo and Talarl (1976) suggested that even with little or no attrition, alveolar bone growth resulted in an increase in face height. Where changes in face height with advancing attrition were not evident, attrition and the compensatory changes were probably balanced, while in populations where reduction of face height is seen, the rate of attrition must have exceeded the rate at which compensatory eruption and alveolar growth occurred.

Campbell, Hackett and Gray (1936), in a study of subjects from central Australia, found that gnathion-nasion height remained constant with age in females and increased slightly in males. The mean gnathion-nasion height for males aged 17 to 25 years was 111.98 mm compared with 114.55 mm in males over 45 years of age. In contrast, Murphy (1959c), in a study of anterior face heights in skeletal material from southern Australia, found that face heights in both males and females decreased with advancing attrition. There was clear evidence, however, of compensatory changes acting to balance, in part, the loss of dental crown height. Referring to the observed loss of dental crown height, Murphy concluded that:
"... continuous eruption compensates for about half. Of this mechanism of continuous eruption, about two-thirds is accounted for by differential alveolar bone deposition with socket shallowing, and about one-third probably by cement apposition with root lengthening. Additional compensation to the extent of about one-tenth of the total loss is provided by general alveolar bone deposition with a bodily shift of the sockets and their contents towards the occlusal plane. Of the total loss as measured in the occlusal position about one-third remains uncompensated."

In addition to the changes in anterior face height, a number of other features of craniofacial morphology have been shown to be related to attrition. In many cases these are secondary to the loss of anterior face height. Fishman (1976), for example, described differences in a number of variables measured on lateral cephalometric radiographs of groups of American Indian subjects with progressively higher attrition scores. In subjects with advanced attrition maxillary alveolar prognathism increased, indicating a forward positioning of the maxillary incisors which was most likely the result of displacement rather than tipping, since the inclination of upper incisors to the anterior cranial base did not change. In addition, the gonial angle decreased and the inter-incisal angle increased with more extensive attrition. This occurred without any significant change in the inclination of the lower incisors to the mandibular plane. Measures of the vertical position of both the maxillary incisors and first molars decreased, indicating a superior repositioning of these teeth. The orientation of the occlusal plane did not alter significantly, however, implying a similar displacement of both incisors and molars. The nasion-sella-first molar angle, representing the antero-posterior relationship of the first molars, also decreased as the degree of attrition increased, suggesting that the first molars moved anteriorly.
Not all observations of facial morphology support Fishman's conclusions, however. Begg (1965), like Fishman, observed that the interincisal angle increased with advancing attrition. He suggested that this was the result of retroclination of the maxillary incisors and proclination of the mandibular incisors together with the anterior migration of the mandibular dentition, rather than due to changes in the gonial angle. Begg suggested that this produced the edge-to-edge incisor relationship commonly seen in subjects with extensive tooth wear. However, Fishman, Lysell (1958) and Mohlin, Sagne and Thilander (1979) all found that the axial inclinations of maxillary incisors did not change with advancing attrition, so that the exact explanation of the observed incisor changes remains unclear. In addition, there were a number of differences in the maxillary and mandibular changes described by Fishman and by Mohlin et al. (Figure 36). Both studies showed a considerable reduction in total face height with advancing attrition, but in the American Indian sample described by Fishman this was accompanied by maxillary protrusion and a superior relocation of the occlusal plane without any change in its orientation. Changes in the maxilla were much less marked in the Swedish population, where both the occlusal and mandibular plane angles decreased and a degree of mandibular protrusion was evident in the older group. The exact reasons for these differences are not clear.

A tendency toward mandibular protrusion in conjunction with loss of face height, similar to that described by Mohlin et al. (1979), has often been observed in dental patients with loss of molar teeth or unsatisfactory dentures. D'Amico (1961) suggested that the relatively anterior position of the symphysis commonly seen in these cases was the result of the loss of anterior face height associated with extensive tooth wear. He concluded that:
"Clinical observation and tests on patients with an edge to edge relation of the anterior teeth because of extensive attrition of the natural teeth have shown that no forward drift of the condyles in the glenoid fossae occurs. The center of vertical rotation of the condyles ... remains constant as the vertical relation of the mandible is opened or closed."

He also concluded that there was no anterior migration of the mandibular teeth.

Anterior repositioning of the mandible may also contribute to the development of the edge-to-edge relationship of incisors and the relative protrusion of the symphysis seen in subjects with advanced attrition. Cross-sectional material is not entirely suitable for the investigation of morphological changes of this type, however, and longitudinal studies over the age range required would be impractical.

Methods

The relationship between attrition and craniofacial morphology was investigated in two ways. Firstly, correlations between attrition scores and each of the craniofacial variables were calculated. Because of the size of the matrix, interpretation of the pattern of correlations was approached in the following way. Initially, correlations between each of the craniofacial variables and attrition scores for left and right teeth were compared. Where only one of the two correlations was significant the relationship was assumed to have arisen as a result of some local factor. The pattern of correlations between each of the craniofacial variables and attrition scores for adjacent and opposing teeth was also examined. When significant correlations were seen for
both left and right teeth but these did not conform to the pattern seen for neighbouring teeth, the relationship was also assumed to have arisen as the result of local factors. In both cases these associations were not given a high priority. This approach emphasised more general relationships providing a method for the systematic exclusion of statistically significant but relatively uninformative correlations.

Examination of the total correlation matrix suggested that correlations between craniofacial variables and maxillary canines tended to reflect the pattern for anterior teeth while correlations involving the maxillary first molars reflected the pattern for posterior teeth. For this part of the study, data for the maxillary right canine and first molar were therefore taken as indicators of anterior and posterior attrition respectively.

The relationship between craniofacial morphology and the rate of attrition (described by residual attrition scores) was also investigated. The maxillary right second molar was selected to represent scores for posterior teeth as the first molar was involved in calculation of the residuals.

In addition, both the male and female populations were divided into high and low attrition score groups. Subjects with attrition scores of less than 0.20 for the maxillary right canine were assigned to the low anterior attrition group while subjects with scores greater than or equal to 0.20 for this tooth were assigned to the high anterior attrition group. Similarly, subjects with scores of less than 0.30 for the maxillary right first molar were assigned to the low posterior attrition group while those with attrition scores greater than 0.30 for that tooth were assigned to the high posterior attrition group. The
means for each of the craniofacial variables considered were compared between high and low attrition groups for both anterior and posterior teeth. This provided a method to verify the pattern suggested by the correlation coefficients and in addition facilitated comparison with previous studies.

Results

Correlations between craniofacial variables and attrition scores for each tooth are shown in Appendix 6. These correlations suggested that the strongest relationship was between attrition and variables reflecting loss of anterior face height, and that this relationship was stronger in males than in females (Table 78). Correlations between upper face height and attrition were not significant in either males or females. Lower face height, however, decreased significantly in males but only slightly in females, as attrition scores increased.

Of the components of lower face height, the strongest correlations (r=-0.61 to -0.77) were between attrition and interalveolar height, which decreased markedly with advancing attrition. In females, both maxillary and mandibular heights tended to increase with attrition, possibly a result of the compensatory changes described previously. In males, however, mandibular height tended to increase but maxillary height decreased in subjects with higher attrition scores.
Correlations between maxillary prognathism and attrition were not significantly different from zero in either males or females. Mandibular prognathism did not appear to be related to attrition in females, but in the male group mandibular basal and alveolar prognathism increased significantly with attrition. Similarly, the occlusal and mandibular plane angles decreased significantly in males but not in females.

Gonial angle, which has been shown in previous studies to decrease with advancing attrition, did not change significantly in the Narrinyeri population. In fact the tendency was for the gonial angle to increase slightly with attrition in males. Facial breadths showed the same relationship with attrition as they did with age, tending to increase in males but decrease in females as discussed in Chapter 9.

The comparison of face heights in low and high attrition groups disclosed a similar pattern of morphological change (Table 79). In females the reduction in lower face height was less than the loss of interalveolar height, suggesting the presence of some compensatory mechanism acting to maintain face height. This appeared to involve changes in maxillary height which was 1.2 mm greater on average in the high attrition group than in the group with low attrition scores. For males, however, the overall loss of lower face height was greater than the loss of interalveolar height despite a relatively greater mandibular height in the group with extensive attrition.

The marked reduction in lower face height in males was reflected in measures of both occlusal and mandibular plane angles and in measures of facial prognathism. The occlusal plane angle, for example, was
11 degrees less in the high anterior attrition group than in the group with low anterior attrition scores. In females, there was a small increase in occlusal plane angle between the two groups. Similarly, mandibular alveolar and basal prognathism were greater in the high attrition group in males, reflecting the tendency for mandibular protrusion with loss of face height in males. Subjects illustrating the general pattern of changes in males and females are shown in Figure 37.

Correlations between residual attrition scores (reflecting the rate of attrition) and craniofacial variables are presented in Appendix 6. Selected correlations are also shown in Table 80. They show a similar pattern to that seen in the correlations with actual attrition scores. Comparing mean scores for these facial variables between groups with positive and negative residual scores (reflecting relatively rapid and relatively slow attrition respectively), highlighted the significant differences between males and females in the changes in maxillary height (Table 81). In males, the mean maxillary height was 3.9 mm less in subjects showing rapid compared with slow attrition, whereas in females the rapid attrition group showed slightly larger maxillary heights on average (+1.4 mm) than the group in which the anterior teeth tended to wear more slowly.

Discussion

In general the Narrinyeri population showed changes similar to those described in other populations with rapidly progressing dental attrition. There was evidence of a reduction in interalveolar height and associated compensatory changes in alveolar heights. On average, the rate of attrition exceeded the rate of compensatory change, however, and as a result lower face height tended to be smaller in subjects with higher attrition scores.
The marked sex difference in the relationship between attrition and face height which was evident in the Narrinyeri population has not been described in previous studies, although neither Fishman (1976) nor Mohlin et al. (1979) analysed male and female subjects separately. Murphy (1959c) described a very similar pattern to that seen in the Narrinyeri females in his female sample which included a number of the same subjects studied here. In both studies, the loss of lower face height in females was about 20 percent less than the loss of interalveolar height, providing evidence of the action of compensatory changes tending to maintain face height. In both the Narrinyeri population and the group studied by Murphy, the difference in interalveolar height between high and low attrition groups was slightly greater in females than in males, perhaps a reflection of the generally greater rate of attrition in females (see Chapter 6).

The male Narrinyeri subjects showed a different pattern of change to that seen in the female group. For females, the loss of lower face height was less than the loss of interalveolar height, whereas in males the difference in lower face height between high and low attrition groups exceeded the decrease in interalveolar height. There was evidence of a compensatory increase in mandibular height (which was greater than that in females) but maxillary height in the male group with more rapid attrition was significantly smaller than in the low attrition group. Because the loss of maxillary height exceeded the increase in mandibular height, the reduction in lower face height was greater than the loss of interalveolar height.
This reduction in lower face height in the male group was associated with changes in the orientation of the occlusal plane and the development of more marked mandibular prognathism. This was similar to the pattern in the medieval Swedes described by Mohlin et al. (1979) who noted that the occlusal plane became more horizontal and that mandibular prognathism increased in older subjects with greater attrition.

The observation that the gonial angle did not change significantly with advancing attrition is evidence that change in mandibular position of the type described by D'Amico (1961) was a factor in the development of the greater mandibular prognathism seen in the high attrition group. The observed reductions in mandibular and occlusal plane angles would be consistent with changes of this type.

To determine whether the relatively anterior position of the mandible which was observed in males with extensive attrition was entirely the result of reduced anterior face height as suggested by D'Amico, the simple geometric model shown in Figure 38 was considered in groups of male subjects with high and low anterior attrition scores. The additional linear dimensions n-cd and cd-ld not discussed previously were obtained by the methods described in Chapter 9. If the distances n-cd and cd-ld remained constant as D'Amico suggested, and the distance n-ld decreased by 6.1 mm from 87.8 mm in the low attrition group to 81.7 mm in the high attrition group, the angle at nasion should increase from 75.6 degrees in the low attrition group to 79.0 degrees in the high attrition group, an increase of 3.4 degrees (Table 82).

The observed angle at nasion was 81.1 degrees, however, suggesting that factors other than the simple loss of anterior face height proposed
by D'Amico's model contribute to the difference in mandibular
prognathism in the high attrition group. Loss of face height alone would
appear to account for about 60 percent of the observed change in the
s-n-lld angle. The difference between the amount of anterior
displacement of the symphysis due to loss of anterior face height alone
and the observed degree of anterior displacement is probably the result
of either small increases in mandibular length with age, or the adoption
of a more anterior posture of the mandible in subjects with loss of
anterior face height. The exact nature of this change remains
unexplained at present, however.

The changes in craniofacial morphology in American Indians
described by Fishman (1976) were quite different from those observed in
the Narrinyerl subjects and those described by Mohlin et al. (1979) in
Swedes. In the American Indians, maxillary prognathism rather than
mandibular prognathism increased with advancing attrition and the gonial
angle tended to be smaller in subjects with high attrition scores. In
addition, while the mandibular plane angle decreased, the orientation of
the occlusal plane remained constant but was situated more superiorly in
the high attrition group. The absence of any change in mandibular
prognathism or in the occlusal plane orientation excludes the
possibility that these changes were associated with mandibular rotation.
The change in gonial angle and the greater maxillary protrusion in the
high attrition group suggests that the pattern of change is more complex
than in the Narrinyerl and Swedish groups.

The observed differences between populations could be real and
reflect important functional and morphological differences between the
groups. They could also arise in a number of other ways, however. All of
the studies have employed relatively small sample sizes and so the
differences might be explained by random variation between the samples. The fact that the results based on the smallest sample size differed markedly from the results in the two studies with the larger sample sizes supports this view.

Because all the studies discussed were cross-sectional, it is difficult to exclude the possibility that at least some of the observed differences in facial morphology between high and low attrition groups were the cause, rather than the result, of the extensive attrition. It could be argued, for example, that since muscle forces are known to be greater in subjects with smaller mandibular plane angles (Ingervall and Thilander, 1974; Ingervall and Helkimo, 1978), the described relationship between mandibular plane angle and high attrition scores was the result of more rapid attrition in subjects exerting greater masticatory forces.

The strong relationship between age and molar attrition (Chapter 5) is evidence, however, that factors such as facial morphology are relatively unimportant in determining the rate of molar attrition. To a large extent the observed changes in facial morphology appear to result from, rather than cause, the extensive molar attrition. The finding that both the correlation analysis and the comparison between means of high and low attrition groups showed the same pattern for both anterior and posterior teeth implies that the relationship between craniofacial morphology and anterior attrition arises in a similar way.

Whether the significantly smaller maxillary height in Narrinyeri males with high attrition scores was the result of the relatively small sample involved or reflects a true difference between male and female compensatory mechanisms is not clear. It is possible that the
difference might be related to the specific pattern of attrition in males and females. Whereas attrition was generally more rapid in females, the maxillary anterior teeth tended to wear more quickly and show greater variation in males than in females (Chapter 6). The relatively rapid reduction in crown height in this region, perhaps associated with the use of these teeth for a variety of non-masticatory purposes, might explain the reduction in alveolar height in this region. The significant negative relationship between residual attrition scores for the maxillary canine and maxillary height in males is evidence of a more rapid rate of attrition in subjects with smaller maxillary heights. This suggests that a simple cause and effect relationship between the variables involved does not exist.

In the Narrinyeri population, compensation for the loss of dental crown height associated with advancing attrition leads to relatively minor changes in facial morphology in females, whereas in males attrition results in marked changes not only in face heights but also in occlusal and mandibular plane angles and in mandibular prognathism.
Because the functional relationship between the maxilla and the mandible depends on both the temporomandibular joints and contacts between the teeth of opposing dental arches, a number of investigators have predicted a relationship between temporomandibular joint morphology and pathology and the dentition. Although many of the details are not understood, clear associations have been demonstrated between aspects of joint morphology or pathology and a number of dental changes. Other investigators have failed to demonstrate such a relationship.

Koyoumdjisky (1956), for example, reported that in 12th century Hungarian skulls the slope of the articular eminence was positively correlated with the palatal slopes of the maxillary incisors \( r=0.55 \) and with the cuspal slopes of the maxillary first and second molars \( r=0.54 \). More recently, Mongini (1975) related condyle morphology to the pattern of chewing and non-chewing contacts. He concluded that:

"The relation between morphological appearance of the condyle and dental abrasion makes it clear that these two elements are dependent on a single factor, namely the functional pattern adopted by the masticatory apparatus. It is equally clear that abrasion, as one of the factors capable of altering this pattern, plays a substantial part in mechanisms that both cause and control remodelling of the mandibular condyle."

In addition Mongini (1977) showed that remodelling of the condyle was more common in patients with radiographic evidence of condylar displacement, which is often associated with loss of teeth. Similar changes were also seen following occlusal therapy of various types.
(Mongini, 1980). In a number of cases, tomographic records indicated that condyles became more rounded and degenerative lesions showed signs of improvement after occlusal therapy, providing further evidence of a relationship between the teeth and the temporomandibular joints.

Seward (1976) also found a close relationship between temporomandibular joint morphology and dental attrition in the sample of 155 Australian Aboriginal crania he examined. Both eminence height and curvature of the fossa tended to be greater in subjects with little molar attrition than in those with more extensive tooth wear.

Hinton (1981) also investigated the relationship between dental attrition and both articular eminence height and slope. In Australian Aboriginals and Eskimos, eminence height tended to increase as the extent of attrition increased, reflecting the same tendency reported in Australians by Campbell (1925:56). Hinton explained the tendency for eminence height to increase with advancing attrition in terms of Frost's (1964) model of bone remodelling, which predicted that eminence height would increase in groups where the condyle tended to function anteriorly. He found that in other populations eminence height tended to decrease with advancing attrition, but that decreases were only seen in those Australians and Eskimos with extreme attrition scores. Hinton related the observed decreases in eminence height in Australians with extreme attrition scores to the loss of molar teeth, which was relatively rare in Eskimos and subjects showing less tooth wear.

A number of investigators have found that the incidence of degenerative change of the temporomandibular joint is greater in subjects with a number of missing molar teeth. Öberg et al. (1971), for example, found:
"... a statistically significant difference in the occurrence of changes in the temporomandibular joint with ... osteoarthritis of the joint being commoner in individuals with extensive loss of teeth than in those with a full set."

This observation may be evidence of a direct association between tooth loss and joint change, or it may result from the common effect of increasing age on both the teeth and the joints; the matter is not fully understood as yet.

Mechanical principles suggest that greater loads are generated in the temporomandibular joints in cases of molar loss (Heckneby, 1974). Carlsson, Kopp and Öberg (1979) concluded that:

"... from theoretical calculations the functional load in the TMJ is much greater when pressure is applied to the bicuspids than when acting on the molar. Loss of molar support has also been found to be associated with TMJ crepitation and accordingly osteoarthritis of the TMJ in patients with TMJ disorders. These findings indicate that an increased functional load caused by loss of molar support is one of the factors responsible for development of osteoarthritis of the TMJ."

Unilateral and asymmetrical function have also been implicated in the aetiology of degenerative changes in the temporomandibular joint. Boering (1966), for example, claimed that:

"... a unilateral chewing habit is the most important factor in the development of temporomandibular joint arthritis".
Similarly, Griffin et al. (1979) found that osteoarthritis of the temporomandibular joint was associated with asymmetrical tooth wear. They concluded that:

"Osteo-arthritis of the TMJ was much more prevalent in cultures exposed to stringent living conditions and generally more severe in those cultures with well worn dentitions. In the sample studied it was apparent that the premature loss of teeth or occlusal imbalance were important factors in the aetiology of the disease."

A number of other investigators have also found a relationship between attrition and degenerative changes in the temporomandibular joint. Brown (1965a) described osteoarthritis in the temporomandibular joints of Australian Aboriginals which he found was accompanied by marked tooth attrition. Similarly, Moffett (1974) described "primary osteoarthritis due to overuse" in archaic American Indians which was "characterised by extensive dental attrition and ... a high incidence of temporomandibular joint osteoarthritis."

Again it is not clear whether the association between attrition and joint change is a causal relationship, or simply the result of the common association between age and both the extent of attrition and the occurrence of joint change. Recent evidence suggests, however, that both the absolute extent of tooth wear and the rate of tooth wear are clearly related to the presence of degenerative lesions (Richards and Brown, 1981).
Methods

The relationships between temporomandibular joint morphology and pathology and both the extent and relative rate of dental attrition and the direction of wear of the mandibular molar teeth were investigated in a number of different ways depending on the nature of the data. Relationships between variables measured on continuous scales were assessed by product-moment correlations.

To assess the relationship between attrition scores and condyle morphology and remodelling, subjects were divided into groups based on attrition scores for maxillary canines and first molars. Subjects with scores of less than 0.2 for the maxillary canine were assigned to the low anterior attrition group and the remaining subjects allocated to the high attrition group. Similarly, subjects with maxillary first molar attrition scores less than 0.3 were assigned to the low posterior attrition group and the remainder were regarded as showing high posterior attrition scores. The sample was also divided into rapid and slow anterior attrition groups based on the residual attrition scores for the maxillary canine. Subjects with positive residual attrition scores were assigned to the rapid group and others assigned to the slow attrition group. To investigate the relationship between condyle morphology and remodelling and the orientation of the occlusal surfaces of the mandibular molar teeth, the sample was divided into 2 groups, the first with occlusal surface directions less than the mean for the population considered and the second with occlusal surface directions greater than or equal to the mean.
The distributions of remodelling scores and condyle types in groups with high and low attrition scores, rapid and slow anterior attrition, and in the groups based on occlusal surface directions, were compared by either the Chi-square test or the sign test depending on the hypothesis being tested. For this analysis, only the relationships between ipsilateral teeth and temporomandibular joints were described. The relationship between contralateral joints and teeth was also considered but, due to the symmetry of both attrition and joint morphology and pathology, they generally showed the same pattern of associations as comparisons between ipsilateral pairs. The differences between mean attrition scores, residual scores and occlusal surface directions in normal and affected subjects were also assessed using Student's t-test.

Results

Joint Morphology

For subjects with no evidence of degenerative joint change of the surface considered, correlations between the linear and angular measures of temporomandibular joint morphology and attrition scores for each tooth are presented in Appendix 7. With the exception of the relationships involving the right eminence slope in males, there was a tendency for articular eminence slope to be greater in subjects with higher attrition scores for anterior teeth, reflecting the trend described by Hinton (1981). With the exception of the right side in males, correlations between both eminence slope and attrition scores
were generally positive, ranging from -0.11 to +0.88. However, the
generally small sample sizes complicated interpretation of the
significance of this relationship.

The orientation of the long axis of the condyle was related to
attrition scores in both males and females, although the pattern in the
sexes was different. In males, correlations between attrition scores
and the condyle orientation in the transverse plane were generally
negative, suggesting that a reduction in the transverse orientation of
the condyle was associated with increasing attrition scores. For
females, there appeared to be no consistent pattern in the correlations
between attrition and the orientation of the condyle in the transverse
plane, but correlations between the orientation in the frontal plane
were generally negative, implying that decreases in the inclination of
the long axis of the condyle in the frontal plane were associated with
higher attrition scores in females. There was no consistent pattern in
the correlations between condyle dimensions and attrition scores.

Correlations between the residual attrition scores, indicating the
relative rate of attrition, and joint variables are shown in Appendix 7.
The relationships were not as clear as between the absolute attrition
scores and joint variables, however. The only consistent relationship
was between anterior attrition scores and the orientation of the condyle
in the frontal plane in males. The tendency was for larger residual
attrition scores to be associated with increases in the inclination of
the condyle in the frontal plane.

The distribution of temporomandibular joint remodelling differed
significantly between subjects with high and low attrition scores (Table
83). In both males and females, posterior remodelling of the condyle
tended to be uncommon in subjects with higher attrition scores, and similarly medial remodelling was less common in females with high attrition scores. However, there was no obvious relationship between joint remodelling and the residual attrition scores (Table 84).

Similarly, there were no significant differences in the distribution of condyle shapes between subjects with high and low attrition scores (Table 85). In females, there was a tendency for condyle Type 2 (remodelling of both medial and lateral anterior surfaces) to occur in subjects with low attrition scores. In males, condyle type 5 (flaring of the lateral anterior surface with a convex medial pole) tended to be more common in subjects with low attrition scores. There was, however, no apparent relationship between the distribution of condyle types and residual attrition scores (Table 86).

Correlations between the directions of the occlusal surfaces of the mandibular molars and each of the linear and angular measures of temporomandibular joint morphology are shown in Appendix 7. There was a relatively strong association between the direction of the occlusal surface of the third molars and the slope of the articular eminence on the same side in females, but other associations were relatively weak (Table 87). The only other consistent pattern was in the relationship between wear directions and the orientation of the condyle in the transverse plane, which was more marked in females than in males.

There did not appear to be any significant differences between the distributions of remodelling in groups of subjects with wear directions less than or greater than their respective means (Table 88). The relationships between condyle morphology and the directions of the occlusal surfaces were difficult to interpret, however, because of the
small samples of subjects with the more uncommon condyle types (Table 89). Condyle type 3 (flattened lateral pole with convex medial pole) was more common in subjects with smaller scores for occlusal surface directions, suggesting that when the occlusal surfaces of the mandibular molars tended to be more lingually inclined than average, condyle Type 3 was more common. This trend was most evident in females where, in the case of the second molars for example, 22 of the 30 subjects with condyle Type 3 had occlusal surface direction scores less than the mean.

It was not possible to investigate the relationship between symmetry in tooth wear and condylar remodelling and morphology because of the limited size of the sample. Of the 30 subjects with sufficient teeth to enable the calculation of asymmetry scores for the observed pattern of attrition, only 13 did not show evidence of degenerative changes in the temporomandibular joint. Of this 13, only 4 showed asymmetry in condyle morphology so that examination of the relationship between joint remodelling and asymmetry in attrition was not possible.

Joint pathology

Mean attrition scores for teeth from the right side in both normal and affected subjects are shown in Table 90. Except in the case of the incisor teeth, where sample sizes were small, there was a clear tendency for attrition scores to be greater in affected subjects than in normal subjects. In the male group, there were sufficient affected subjects to allow division into groups mildly and severely affected by degenerative changes of the temporomandibular joint. Attrition scores generally increased with the degree of severity of joint change.
There were no significant differences between mean residual attrition scores for normal and affected groups (Table 91). In females there was, however, a consistent trend for larger residual scores for incisors, canines and premolars in affected subjects. In males, there was evidence of a similar trend for the maxillary anterior teeth but not for the mandibular anterior teeth. For most teeth the variation in residual scores was greater in the affected groups than in the normal group.

Differences in the directions of the mandibular occlusal surfaces between normal and affected subjects are shown in Table 92. The occlusal surfaces of the mandibular molars were more buccally inclined in affected subjects, perhaps due to the difference in age between normal and affected subjects.

To assess the relationship between symmetry in tooth wear and joint change, mean differences greater than 0.05 between attrition scores for left and right teeth were considered to indicate predominantly right sided wear, and scores less than -0.05 to indicate predominantly left sided wear. Twenty of the 30 available subjects showed symmetrical wear. Of the 10 showing asymmetrical wear, 3 had heavier wear on the right side and 7 had heavier wear on the left. Of these 10 subjects, 6 showed signs of degenerative change in one or both temporomandibular joints and 4 were unaffected.

Among affected individuals in general, there was a tendency for subjects with symmetrical tooth wear to also show symmetrical joint change; of the 11 affected subjects with symmetrical tooth wear, 8 also showed a symmetrical pattern of joint change while of the 6 subjects
with asymmetrical attrition only 2 showed a symmetrical pattern of joint change. Although the sample was small, the observations are consistent with trends reported in previous studies.

Discussion

Investigation of the relationship between dental attrition and temporomandibular joint morphology is complicated because both are obviously age dependent and it is difficult to assess the direct effect of attrition on the joint. The bias introduced into the sample by excluding affected subjects also complicates interpretation of the results in some instances. In addition, a number of the observed relationships may have arisen indirectly, as a result of the methods of measurement.

For example, the commonly observed remodelling of the lateral pole of the condyle in the Narrinyeri population might explain the changes in the orientation of the condyle which were apparently related to attrition. This could be an artifact of the method of measurement, as the lateral extremities of the left and right condyles were used as reference points for the measurement of the condyle orientation. With the remodelling of the lateral pole of the condyle this reference would be displaced inferiorly and distally and therefore apparently smaller angles would result. The decreased transverse condyle orientation in males with more extensive attrition, and the smaller orientation in the frontal plane in females with high attrition scores, may have arisen in this way.
A number of important relationships between attrition and both temporomandibular joint morphology and pathology were evident in the Narrinyeri population. With the exception of the slope of the right articular eminence in males, eminence slopes in subjects with no evidence of degenerative joint change tended to increase with increasing anterior attrition. Although the precise relationship between the pattern of tooth wear and the morphology of the condyle is not clear, the observations appear to be consistent with those of Mongini (1975) who found that the morphology of the condyle was related to the pattern of chewing and non-chewing side contacts. He suggested that:

"The roundish shape ... (of the condyle) ... with symmetrical slopes is typical of young subjects with unimpaired arches and little or no abrasion. Remodelling is still of limited extent. Function and consequent abrasion lead to characteristic changes of shape, due to such remodelling. If abrasion is more or less evenly spread over both the working and balancing component and occlusal surfaces assume the form of a mortar, the condyle tends to have ... markedly overhanging slopes. If the working component is primarily involved, either or both condylar slopes are flared and flattened."

The observed difference between the frequencies of the various condyle morphologies in Mongini's (1975) sample and that seen in the Narrinyeri population appeared to reflect functional differences between the groups. Mongini found that when tooth contact was predominantly on the chewing-side, flattening of either the medial or lateral pole of the condyle was more common, while symmetrical changes were associated with a higher proportion of non-chewing side contacts. He also found that changes in the anterior-medial surface occurred more often in cases where the medial pole was more prominent.
The heavy attrition seen in the Narrinyeri population has been shown to be related to the progressive loss of non-chewing side contacts (Chapter 8). This was consistent with the relatively low frequency of symmetrical condyle types (Types 1 and 2) seen in the Narrinyeri population. In addition, Narrinyeri subjects rarely showed negative condyle orientation in the frontal plane which, according to Mongini, was associated with more frequent remodelling of the anterior-medial surface of the condyle. Remodelling of the lateral pole of the condyle was common in the Narrinyeri population, with 51.9 percent of the subjects showing lateral flattening of the condyle (Type 3) compared to 13.0 percent in Mongini's sample, where the medial condylar pole was frequently more prominent. It would appear that although Mongini studied a sample with significantly less attrition than was found in the Narrinyeri, his conclusions are consistent with the results of this study.

The appearance of degenerative changes in the temporomandibular joints of Narrinyeri subjects was related to the pattern of tooth wear in a similar way to that described in other groups by Griffin et al. (1979). Subjects with a symmetrical pattern of tooth wear tended to be either unaffected by degenerative joint change or showed bilateral lesions, whereas those with symmetrical tooth wear generally showed lesions bilaterally. Subjects with asymmetrical attrition more commonly showed unilateral joint involvement.

It is not entirely clear if these associations reflect a causal relationship between asymmetry in tooth wear and the pattern of joint change. While it has been suggested that degenerative joint changes are the result of unilateral function, the possibility that a unilateral
functional pattern could be adopted by subjects with degenerative change in only one joint cannot be overlooked. Subjects with unilateral lesions would tend to chew on the affected side to reduce the distance travelled by the affected condyle, and as a result attrition scores for the affected side could be higher. Alternatively, it could be argued that because joint forces would be greater on the non-chewing side, a unilateral chewing pattern could result in degenerative change on the non-working side, so that subjects with a preference for chewing on one side would show joint changes in the opposite joint. It is difficult to differentiate between these two possibilities by cranial examination alone.

Although subjects with no evidence of degenerative change showed an increase in eminence slope with increasing attrition scores, when the population was considered as a whole, degenerative joint disease was more common in those individuals with high attrition scores. In addition, residual attrition scores for anterior teeth in females and for maxillary anterior teeth in males also tended to be larger in affected subjects than in normal individuals. There are many aspects of the relationship between joint morphology and attrition which are poorly understood. The data for the Narrinyeri population appears, however, to support the previous suggestion that both the extent and the rate of attrition are important in the development of degenerative joint change (Richards and Brown, 1981).
CHAPTER 14

CRANIOFACIAL MORPHOLOGY AND THE TEMPOROMANDIBULAR JOINT

A number of investigators have predicted associations between temporomandibular joint form and function and the morphology of the facial structures. It has been argued that the close relationship between the morphology of the facial skeleton and the direction of action of the various masticatory muscles determines, in part at least, the pattern of movement of the mandible which in turn is said to influence the morphology of the temporomandibular joint.

Angel (1948), for example, proposed "that bony and muscular structure ... and method of chewing mainly shape the temporomandibular joint through the effects on function." He was, however, unable to establish this relationship and was led to conclude that:

"... in formation of the adult temporomandibular joint genes appear more important determinants than environment since the joint is related as much to the multiplicity of factors in the genetically determined total facial pattern as to the few factors in the learned chewing pattern."

Since then Ricketts (1950, 1953) and Lundberg (1963) have described fossa depths in subjects with different types of malocclusions. In each study, articular eminence heights were smaller in subjects with Class III malocclusions than in normal subjects. In addition Lundberg described greater articular eminence heights in subjects with larger anterior overbite, although Lindblom (1960) and Ingervall (1972) did not find this relationship.
Only Ingervall (1974) has been able to clearly demonstrate
associations between facial morphology and articular eminence height.
He found that:

...a distinct interdependence between the height of the
tubercle and certain facial morphological characteristics.
Above all there appeared to be a correlation between the
height of the tubercle and the inclination of the face,
especially that of the lower face. In persons with a tendency
to parallelism between the anterior cranial base, the nasal
line, the maxillary occlusal line and the mandibular line, the
tubercle tends to be high. Such cases are characterised by a
rectangular facial form in profile with great posterior height
of the face and marked curvature of the mandible and of the
cranial base. This form of face is also characterised by
considerable depth of the face and total prognathism. The
height of the tubercle is small in the opposite type of face."

In view of the probable relationship between the normal and
pathological anatomy of the temporomandibular joint, the muscle forces
acting on the joint surfaces and facial morphology, a closer examination
of the association between these variables is warranted.

Methods

The relationship between facial morphology and the morphology of
both the temporal fossa and mandibular condyle was assessed in two ways.
Coefficients of correlation between each of the metric joint variables
and all of the craniofacial variables were considered. Initially, the
relationships were considered for left and right sides separately.
Where only one of the two correlations was significant the relationship
was assumed to have arisen by chance and was not considered in detail.
This procedure assisted in the interpretation of the correlations.
To assess the relationship between facial morphology and both the extent of condylar remodelling and the overall shape of the mandibular condyle, the distributions of condyle types in groups of subjects with scores either less than, or greater than or equal to the mean for each of the facial variables were compared. In some cases sample size prevented testing of distributions, but where possible either Chi-square tests or Sign tests were applied to determine the significance of differences in the distributions between groups.

To investigate the relationship between facial morphology and temporomandibular joint pathology the sample was divided into a normal and an affected group. The normal group consisted of subjects with no evidence of pathological change on any joint surface; subjects with any evidence of degenerative change were included in the affected group.

Data obtained in this way were subjected to three types of analysis. Mean scores and standard deviations for each of the craniofacial variables were calculated for the normal and affected groups and compared using Student's t-test. For comparison with the joint morphology data, contingency tables relating the distributions of cranial and facial variables in normal and affected subjects were considered. It is possible, however, that consideration of mean scores might not reveal important trends if, for example, affected subjects tended to show unique combinations of scores for a number of variables, or if the scores for normal subjects were nearer to the population mean and affected subjects showed scores at both extremes of the range. In the second case, this should be evident on examination of variances for the variables involved, but would not be clear in comparisons of mean scores or from contingency tables. For this reason, each subject was
examined separately and groups of similar subjects were considered, to
determine whether facial morphology and the presence of degenerative
to changes in the temporomandibular joint were associated.

Results

Joint morphology

Correlations between each of the craniofacial variables and
measures of both left and right temporomandibular joint morphology are
shown in Appendix B. In males, significant positive correlations were
found between both right and left eminence slopes and mandibular ramus
height, palate length and symphysis height. In addition, eminence
slopes were negatively correlated with mandibular alveolar prognathism.
This was similar to the relationship described by Ingervall (1974), who
found that eminence slope was related to posterior face height and
facial prognathism. Subjects illustrating the relationship between
facial morphology and eminence slope are shown in Figure 39a.

The pattern was different in Narrinyeri females, however.
Correlations between eminence slope and ramus height, palate length,
symphysis height and facial prognathism were all small and not
significant. Eminence slope, however, showed a significant negative
correlation with mandibular ramus breadth and was positively correlated
with nasion-prosthion length. Subjects illustrating this relationship
are shown in Figure 39b.
In both males and females, the antero-posterior and medio-lateral dimensions of the mandibular condyle were significantly correlated with a number of craniofacial variables. The antero-posterior diameter of the condyle showed a positive correlation with ramus breadth and a negative correlation with facial plane angles and with gonial angle. In addition, in females, larger antero-posterior dimensions were seen in subjects with smaller palate breadths and larger total cranial base lengths. It would appear that, in general, larger condylar dimensions were associated with variables which reflect general muscularity and the generation of large muscle forces (see Chapter 9).

In males, the orientation of the condyle in both the frontal and transverse planes was not closely related to any of the craniofacial variables. The only significant correlation was between the orientation of the condyle in the transverse plane and the mandibular plane angle. In females, however, a number of the craniofacial variables were significantly correlated with the orientation of the condyle in the frontal plane. Larger angles were associated with larger values for a number of cranial vault dimensions, pharyngeal breadths and a number of mandibular dimensions. In addition there was a strong negative correlation between foramen angle and condyle orientation in the coronal plane. Correlations between transverse plane orientation of the condyle and craniofacial variables were not significant in females.

The distributions of remodelled and non-remodelled posterior, anterior-medial and anterior-lateral condylar surfaces among subjects grouped according to scores for each of the craniofacial variables were considered (Tables 93a,b,c). Despite the relatively small sample of subjects with no signs of temporomandibular joint pathology, a number of
clear associations between facial morphology and remodelling of the mandibular condyle were evident. Remodelling of the posterior surface was more common in males with larger endocranial and nasal breadths, occlusal plane angles and minimum ramus, total and lower face heights. In females remodelling of the posterior condylar surface was also more common in subjects with larger cranial breadths (reflecting the same tendency seen in males) and in subjects with larger foramen angle and palate height (Table 93a).

In the Narrinyeri population, remodelling of the lateral part of the articular surface of the condyle was very common. Only 8 male and 13 female condyles did not show evidence of lateral remodelling. The absence of remodelling was clearly more common in subjects with smaller pharyngeal depth and symphysis angle. For example, 7 of the 8 non-remodelled condyles showed small symphysis angles (Table 93b).

In contrast to the lateral surface, remodelling of the medial pole of the condyle was relatively uncommon in the Narrinyeri population. Only 13 of the 48 available male condyles and 12 of the 58 female condyles showed medial remodelling. This did not appear to be strongly related to many of the craniofacial variables. In females, medial remodelling was more common in subjects with larger total mandibular lengths, while in males the only significant relationship was between medial remodelling and relatively small total and maxillary face heights (Table 93c).

Because only seven mandibular condyles without any evidence of remodelling of the anterior surface were available from the male sample, it was difficult to determine whether the presence of remodelling was related to the facial morphology. The only aspect of condyle morphology
which appeared to be related to facial morphology in males was the
presence of flattening of the anterior-lateral surface in cases where
the anterior-medial surface was convex. This was more common in
subjects with larger total face heights (Table 94). In females,
associations between the absence of remodelling and a number of
craniofacial variables were evident. Remodelling was uncommon in
subjects where maxillary alveolar prognathism, symphysis angle, total
cranial base length and mandibular body thickness were less than the
mean and where naslon-prosthion length was greater than the mean (Table
95).

It was difficult to determine which of the relationships described
here were real and which were artifacts arising from associations with
common factors, since many significant associations involved variables
which were also related to attrition or to the presence of joint
pathology.

Joint pathology

Means and standard deviations of selected craniofacial variables
for normal and affected subjects are shown in Table 96. In both the male
and female groups, affected subjects tended to be older than those with
no evidence of joint change. Similarly the mean interalveolar heights in
both sexes were smaller in affected subjects, perhaps a consequence of
more extensive dental attrition in subjects with evidence of joint
pathology. In females, both total and lower face heights were also
significantly smaller in affected subjects as were a number of other
facial and cranial dimensions. In a number of cases this might be due to
the tendency for smaller dimensions in older female subjects (see
Chapter 9) rather than any direct association between joint pathology
and smaller overall size.
Mandibular ramus dimensions also differed significantly between normal and affected subjects, but the pattern appeared to be quite different in males and females. Affected male subjects showed significantly smaller minimum ramus breadths and only slightly smaller minimum ramus heights than normal subjects. In females, however, minimum ramus breadths in normal and affected subjects did not differ significantly but average minimum ramus heights were markedly smaller (4.4 mm) in affected subjects. This same trend was evident in remodelling changes in females, where subjects with small ramus heights more frequently showed signs of remodelling of the lateral part of the condyle. Mean occlusal plane angles did not differ significantly between normal and affected groups, but in both males and females occlusal plane angles were significantly more variable in the affected groups.

The examination of each subject individually revealed a number of important relationships between facial morphology and joint pathology which were not evident in the grouped analysis of data. Of the 33 affected subjects, 3 showed obvious skeletal abnormalities. These subjects are illustrated in Figure 40a,b,c. It was not possible to determine whether the development of the observed joint changes was related to these skeletal abnormalities, and so these subjects were excluded.

An additional three individuals had dental malocclusions and were also excluded. Subject A40 showed anterior crowding in the maxillary arch and had a congenitally missing mandibular left second premolar. Subject A97 showed an Angle Class III dental pattern and subject A116 had a relatively large overbite and severely crowded mandibular anterior teeth. These individuals are illustrated in Figures 41a,b,c.
Of the remaining 27 affected subjects, 7 showed changes in facial morphology of the type associated with very advanced attrition. In each case, these subjects showed small occlusal and mandibular plane angles, marked mandibular basal and alveolar prognathism and relatively small total face heights (Figure 42a-g). These changes were most common in males, although 2 affected females showed the same tendency. In the male group only subject A38556 did not show joint changes of the most severe type in at least one joint surface.

Twelve of the remaining 20 affected subjects conformed to one of two patterns of facial morphology. One group of 3 males and 4 females showed large occlusal plane angles and face heights but small facial profile angles (Figure 43a-g). No unaffected subjects showed this pattern. A second group of 2 males and 3 females showed the opposite pattern with small occlusal plane angles and face heights and relatively large facial profile angles (Figure 44a-e). In both groups, ramus heights were smaller than the mean for the population. Only one case (A38525) with small occlusal plane angle and face height and large facial profile angles was not affected (Figure 44f). This suggests that, in subjects with small mandibular ramus heights, the combinations of either relatively parallel facial planes and marked facial prognathism or divergent facial planes together with facial retrognathism were associated with the presence of degenerative changes in the temporomandibular joint.

Of the 32 affected subjects there were a further 8 (25 percent) which showed joint changes which could not be related to either of the described facial patterns or to the changes associated with dental attrition (Figure 45a-h).
Discussion

Some features of temporomandibular joint morphology and pathology are clearly associated with various craniofacial variables, although in some cases the association may involve a common relationship between age or attrition. For example, in males the orientation of the condyle in the transverse plane was smaller in subjects with smaller mandibular plane angles. Both mandibular plane angle and the transverse orientation of the condyle tended to decrease with age, however, so that the apparent relationship between the two may well have arisen indirectly.

A number of the significant associations between facial and joint morphology were probably topographical in origin while others were probably the result of regional growth coordination. For example, in both males and females, ramus breadth and the antero-posterior diameter of the condyle were positively correlated. Both are measures of the antero-posterior dimension of different parts of the mandibular ramus, and so a relatively high correlation might be expected.

In addition, a number of other apparently significant associations between aspects of temporomandibular joint morphology and facial morphology were probably a result of the special selection of normal subjects, which was imposed when those with signs of degenerative change were removed from the sample. For example, in males remodelling of the posterior surface of the condyle was relatively common in subjects with large occlusal plane angles, ramus heights and total and lower face heights. This was probably the result of the selective exclusion of subjects with signs of degenerative joint change, who tended to have smaller occlusal plane angles, ramus heights and face heights.
The relationship between facial morphology and temporomandibular joint pathology was most clearly seen in comparisons of the facial morphology of subjects with and without evidence of degenerative changes of the temporomandibular joint. Of the 33 subjects showing degenerative joint change, obvious occlusal abnormalities were evident in 3 cases and 7 subjects showed facial changes typical of very advanced dental attrition. In a further 15 subjects the joint changes were associated with a recognizable facial pattern. In 3 of these cases, some features of the facial morphology were considered to be outside the normal range and the other 12 cases showed features characteristic of one of two "facial types" which, irrespective of the age or sex of the subject, were consistently associated with evidence of degenerative joint change. In the available sample of the Narrinyeri population, all subjects with occlusal plane angles and facial heights greater than the mean and facial profile angles and ramus heights less than the mean, and the majority of those with relatively large facial profile angles and small occlusal plane angles, face heights and ramus heights, showed signs of degenerative changes in one or both temporomandibular joints. In comparison, both males and females showing no evidence of either joint pathology or remodelling tended to show relatively small facial profile and symphysis angles.

With our present knowledge of the physiology of the masticatory system, it is difficult to understand and explain many of the significant relationships observed in the Narrinyeri population but, in general terms, an association between joint morphology and pathology and the pattern of facial morphology was evident in a number of subjects.
Section Five

SUMMARY
SUMMARY AND GENERAL DISCUSSION

Efficient masticatory function depends very much on harmonious relationships between the components of the masticatory system and on the individual’s ability to adapt to the progressive morphological and functional changes that occur throughout life. However, very few detailed descriptions of the associations between the dentition, craniofacial structures and the temporomandibular joints have been reported. The purpose of this study was to investigate the adaptive changes occurring in each component of the masticatory system in response to functional changes brought about by progressive tooth wear.

A sample of skulls representing 74 Australian Aboriginal members of the Narrinyeri group was selected for the study. The relatively rapid dental attrition seen in this population provided evidence of continual, progressive dental change and, in some instances, concomitant changes in the morphology and pathology of the facial structures and temporomandibular joints. As a result of the geographic, temporal and cultural homogeneity of the group, the observed variation represented genetic and environmental effects acting within the population rather than inter-population differences. Furthermore, the measurement of various craniofacial, joint and dental variables was less complicated in skeletal material than it would be in a group of living subjects. However, the use of skeletal material prevented any consideration of soft tissue changes and also complicated the determination of the age and sex of individuals. To overcome the latter problem, methods to estimate the age-at-death of skulls were developed, and previously reported methods for determining sex from observations of crania were
investigated and modified to suit the purposes of the study. Because the study involved an analysis of the sources and patterns of variation within the sample, descriptions of the relevant features of the dentition, craniofacial skeleton and temporomandibular joints were undertaken. This information provided a basis for individual comparisons.

In general, the Narrinyeri dentition conformed to the pattern described for other Australian Aboriginal groups. The teeth were large and showed relatively extensive attrition with teeth wearing more rapidly in females than in males. With few exceptions, tooth wear was symmetrical. Compared with other groups, the breadths of each dental arch and the differences between maxillary and mandibular breadths were relatively large. These differences were greatest in the first molar region and smallest in the region of the third molars, where, in females, arch breadths tended to be slightly larger in the mandible than in the maxilla. The observed arch breadth differences were associated with the progressive development of an "ad palatum" pattern of wear which, in most subjects, resulted in a "helicoidal" pattern of tooth wear. Only in the oldest individuals did this progress to a stage where the occlusal surfaces of all mandibular molars were buccally inclined.

Generally, the craniofacial morphology of the Narrinyeri was similar to that described for other Australian Aboriginal groups, although a number of differences were evident. Compared with other Aboriginal populations, cranial length, facial breadths, ramus breadth and cranial base angle were larger in the Narrinyeri. The gonial angle and posterior cranial base length, however, tended to be smaller. These differences emphasized the greater robustness and muscularity of the Narrinyeri subjects.
Linear and angular measures of temporomandibular joint morphology did not differ significantly from those reported for other groups. Condyle remodelling and degenerative joint changes were common in the Narrinyeri sample: more than 60 percent of male joints and 40 percent of female joints were affected by degenerative lesions while 87 percent of condyles unaffected by degenerative lesions showed signs of remodelling.

This study has helped to clarify the functional relationships between the components of the masticatory system. In the Narrinyeri sample, dental attrition produced a continual, progressive reduction in interalveolar height in both males and females. Although both the overall rate of tooth wear and the rate of reduction in interalveolar height were greater, on average, in females, the loss of lower face height was greater in the male group. Compensatory increases in both maxillary and mandibular alveolar heights acted to maintain lower face height in females, whereas in males interalveolar height and maxillary height decreased with advancing attrition, producing the marked loss of lower face height. As a result of this reduction of anterior face height, the orientation of the occlusal and mandibular planes became more horizontal and mandibular prognathism increased in males. These changes accounted for only 60 percent of the total observed difference in the position of the symphysis, however, implying that either additional bone deposition in the mandible or a more anterior mandibular posture also contributed to the relatively anterior position of the mandible in subjects with severe attrition.
Interpretation of the relationships between the morphology of the temporomandibular joint and the pattern of tooth wear was complicated by difficulties in quantifying observed changes adequately. The high correlations between the direction of wear of the mandibular third molars and the slope of the ipsilateral articular eminence in females indicated a close functional relationship between the teeth and joints which together form the articulation between the cranium and the mandible. There was also some evidence that the articular eminence height increased with advancing attrition in the manner suggested by Hinton (1980). Furthermore, the observed pattern of joint remodelling was consistent with the relationships between dental attrition and condyle morphology described by Mongini (1975).

Clear identification of the association between degenerative lesions of the temporomandibular joint and the extent and rate of attrition is complicated as both attrition and joint disease are age-dependent. However, the evidence suggests that the extent and rate of attrition of the anterior teeth in particular were each associated with the degenerative lesions frequently seen in the Narrinyeri.

The reduction in facial height resulting from attrition was not the only craniofacial change associated with the development of joint lesions. In general, the mandibular ramus height tended to be relatively small in affected subjects and a significant proportion of the affected subjects showed consistent patterns of deviation from the population averages for facial angles and dimensions. Probably in these individuals the altered masticatory function produced unfavourable forces on the joints resulting in the development of degenerative lesions. The key to understanding these relationships lies in studies such as those of
Hylander (1975, 1977, 1978a, 1979a,b) and Brehnan et al. (1981) which have added to our knowledge of the mechanics of the masticatory system. Because of the experimental difficulties involved and the variation between subjects definitive statements are not possible as yet, however.

The present study has provided evidence that substantial adaptive change may occur in the masticatory system in response to the demands imposed by the very harsh conditions under which the Narrinyeri lived. Extensive and rapid dental attrition when combined with functional patterns associated with particular facial morphology produced conditions to which the joints could not adapt. As a result of this combination and sequence of events degenerative changes developed in the temporomandibular joints of many individuals.