AN ANATOMICAL BASIS FOR THE MANAGEMENT OF COMPLEX WRIST INJURIES

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Chapter 1 - INTRODUCTION

1.1 Background

The wrist is a complex association of eight carpal bones linked by ligamentous and capsular attachments to the radius and ulnar proximally and to the metacarpal bones distally. Their associated motion produces the full and stable range of movements collectively known as the wrist joint.

Although many articles have examined the anatomy and function of the carpus, it remains incompletely understood due to the irregularity of their morphological shapes, the multi-planar kinematic rotations and translations, and their small magnitude of movements (Gardner et al., 2006). Despite the importance of the wrist to function, the development of knowledge of the wrist and its disorders has been slow to accumulate.

The wrist has largely been ignored in historical texts, being over-shadowed by other, apparently more appealing anatomical questions. However, over the past 20 years, the advent of new, non-invasive technologies has rekindled interest in the wrist and led to a rapid improvement in our understanding of the normal and abnormal wrist, particularly in the areas of anatomy, imaging and surgery. Our knowledge continues to improve as advances in investigational technologies develop, and advances in one area often provide the basis for development in another. This new knowledge interfaces anatomy with imaging and surgery for the wrist.

1.1.1 Anatomy

Anatomy, the oldest medical science, derives its name from the Greek word anatamnein (to cut, to dismember). The history of anatomy as a science extends from the earliest examinations of sacrificial victims to the sophisticated analyses of the body performed by modern scientists. Over time anatomy has evolved into a respected scientific discipline that now figures prominently in medical education, and a thorough understanding of anatomy is crucial to the field of hand and upper extremity surgery.

The oldest known systematic study of human anatomy is contained in an Egyptian Ebers Papyrus (Figure 1.1) dating from 1600 BC (Coulter, 2001). The papyrus suggests that the
heart, vessels, liver, spleen, kidneys, ureters, and bladder were recognized. However, the papyrus contained no record of any study of the extremities (Lyons, 1978).

The earliest medical scientist, whose work survives in any great part today, was Hippocrates, a Greek physician active in the late 5th and early 4th centuries BC (460 - 377 BC) (Garrison, 1966). He is regarded universally as the father of western medicine and postulated that anatomy served as the foundation of medicine. His work demonstrated a basic understanding of musculoskeletal structure and function and included a treatise *On Fractures* (included instructions explicit to the management of upper extremity fractures) and dislocations in the upper extremity in his tract *On the Articulations*, which included techniques for reduction of a dislocated shoulder, elbow, wrist, and finger. However, much of his work, and that of his students, relied on speculation rather than on empirical observation of the body, and consequently harbored superficial or erroneous ideas about the human body (Shin and Meals, 2005).
It was not until the 4th century BC that Aristotle (384 - 322 BC) and several contemporaries produced a more empirically founded system, based primarily on animal dissection (Garrison, 1966). Two of his works, De partibus animalium (Parts of Animals) and Historia animalium (History of Animals), constitute remarkable anatomic investigations. These studies led Aristotle to declare that the hand, together with reason and speech, was one of the three properties unique to humans (Lyons, 1978). However, these early Greek researchers were limited by the existing laws, customs, and prejudices against the practice of human dissection (Shin and Meals, 2005).

The first empirically-based anatomical research was performed in the 4th century BC by Herophilos (335 - 280 BC) and Erasistratus (304 - 250 BC), who founded the great medical school of Alexandria. Despite the Greeks’ prejudices against the practice of human dissection they were not averse to having dissections performed in one of their conquered territories, namely in the Greek colony of Alexandria in Egypt. Here, under the auspices of the Ptolemaic dynasty, live dissections, or vivisection, were performed on criminals (Garrison, 1966). Herophilos in particular developed a body of anatomical knowledge much more informed by the actual structure of the human body than previous works had been. Herophilos and Erasistratus were credited with assembling the first skeletons for the purposes of studying human osteology, and made important contributions to the science of anatomy (Shin and Meals, 2005).

Many of the accomplishments of these early anatomists were eclipsed by the final major anatomist of ancient times, Claudius Galen (129 - 200 AD) (Coulter, 2001; Garrison, 1966). He compiled much of the knowledge obtained by previous writers, and furthered the inquiry into the function of organs by performing vivisection on animals. Due to a lack of readily available human specimens, discoveries through animal dissection were broadly applied to human anatomy as well (Figure 1.2). His collection of drawings, based mostly on dog anatomy, became the most authoritative text on anatomy in European medical education until the 16th century AD (Figure 1.2) (Coulter, 2001).

Galen devoted a major portion of his work to the anatomy and function of the hand and was first physician and anatomist to do so (Shin and Meals, 2005). In his book De ossibus ad tirones (On Bones for Beginners) Galen used an anatomic nomenclature that included terms like epiphysis, apophysis, phalanx, metacarpus, and carpus, although such terms may not have been coined by him (Shin and Meals, 2005).
The first challenges to the Galenic doctrine in Europe occurred in the 16th century, following the advent of the printing press (Coulter, 2001; Garrison, 1966). Throughout Europe, a collective effort proceeded to circulate the works of Galen and Avicenna, and later criticisms on their works were published. Vesalius was the first to publish a treatise, *De humani corporis fabrica*, that challenged Galen "drawing for drawing" (Figure 1.3). His drawings presented the major discrepancies between the anatomy of dogs and humans, and formed the basis of observational anatomy in the centuries that followed.

Figure 1.2

A late thirteenth-century illustration of the venous system within the body. The majority of the anatomical texts of this time were based on the work of Galen. According to Galen, the venous system was distinct from the arterial, and the blood ebbed and flowed through the body.
The study of anatomy flourished in the 16th and 17th centuries, with the printing press facilitating the exchange of ideas. Many famous artists studied anatomy, attended dissections, and published drawings for money, from Michelangelo (1475-1565) to Rembrandt (1604-1669). During this time and for the first time, prominent universities could teach anatomy through drawings, rather than relying on knowledge of Latin (Garrison, 1966). However, only certified anatomists were allowed to perform dissections, and sometimes then only yearly. These dissections were sponsored by the city councillors and often an admission fee was charged. Many anatomy students travelled around Europe from dissection to dissection during the course of their study, following the availability of fresh bodies (i.e. after a hanging) because, a body would decay rapidly and become unsuitable for examination before the advent of refrigeration (Figure 1.4) (Shin and Meals, 2005).

During the 19th century, anatomists largely finalised and systematised the descriptive human anatomy of the previous century (Coulter, 2001). The intensive interest in anatomical research
created a large demand for materials. Demand for cadavers was so high that “grave-robbing” became common-place. In response to this issue, the English Parliament passed the Anatomy Act 1832, which finally provided for an adequate and legitimate supply of corpses by allowing dissection of destitutes. This enabled a more thorough and controlled investigation into anatomy and culminated in the production of the first comprehensive modern anatomical text, Gray's Anatomy (Figure 1.5). This text remained the gold-standard text for over a century and provided the framework for the development of modern texts used in practice today (Williams, 1989).

Figure 1.4

Rembrandt van Rijn’s The Anatomy Lesson of Dr. Nicolaas Tulp (1632). In this painting the eminent surgeon stands surrounded by students as he demonstrates the workings of the forearm muscles and tendons. Despite debate over the origin of the forearm flexor muscle mass as depicted in this painting dissection of the upper extremity clearly was important to anatomists. (From - Mauritshuis, the Hague).
While increasingly sophisticated anatomical illustrations and atlases have appeared in the 20th century, little has changed in regard to the anatomical descriptions of the musculoskeletal system. Many of the revisions have expanded on the anatomical descriptions, especially in regard to anatomical variations commonly seen at dissection. However, cadaveric investigations are limited in their use, as the majority of the anatomy cannot be visualised without the extrinsic structures being incised and removed. This limits the scope of these investigations, as many of the anatomic and mechanical properties of these structures are compromised. Newer imaging techniques have provided the means for developing non-invasive ways of investigating anatomy and the properties of specific structures, both in-vivo and in-vitro. Indeed, a thorough understanding of modern anatomy relies on the correlation of the progressive cumulative understanding of classical anatomists, arthroscopists and various imaging modalities. While dissection plays an important part in the understanding of the morphology of the carpus, imaging and arthroscopy have improved our understanding of functional anatomy and carpal kinematics.

Figure 1.5
A photograph of Henry Gray, the original author of *Gray's Anatomy of the Human Body*, an English-language human anatomy textbook widely regarded as a classic work on the subject. The book was first published under the title *Gray's Anatomy: Descriptive and Surgical* in the United Kingdom in 1858, and the following year in the United States. While studying the anatomical effects of infectious diseases, Gray contracted smallpox from his dying nephew and died shortly after the publication of the 1860 second edition, at the age of 34. The text has been revised many times and is now in its 39th British edition.
1.1.2 Carpal anatomy

1.1.2.1 Nomenclature

Despite the importance of the wrist to function, the development of knowledge of the wrist and its disorders has been slow to evolve. For centuries the wrist was virtually ignored, often being omitted from anatomy texts until the emergence of investigational anatomy by Vesalius (Moes, 1976). In 1543, Andreas Vesalius presented the first drawings of the wrist bones in *De Humani Corpis Fabrica* (On the Fabric of the Human Body) (Figure 1.3). In this text, Vesalius named the carpal bones from scaphoid to pisiform as 1 through 4, and from trapezium through to the hamate as 5 through 8 (Figure 1.6) (Dobyns and Linscheid, 1997). The nomenclature of the carpal bones first appeared in 1653, when the anatomist Lyser named the bones of the distal row from radial to ulnar as trapezoids, trapezium, os magnum and unciforme, and the proximal row from ulnar to radial he called pisi, cuneiforme, lunatum, and scaphoides (Dobyns and Linscheid, 1997). The present nomenclature was proposed by McMurrich (1914). He also noted that the centrale forms a portion of the distal scaphoid in humans. The *Nomina Anatomica* adopted the McMurrich version in 1955 (Johnson, 1990).
A theory on the complex movements of the carpus was first proposed by Reuleaux in 1875, kindling interest in the mechanical descriptions of the carpus (Dobyns and Linscheid, 1997). However, it was not until the advent of X-ray in 1895, that new, more detailed mechanical descriptions of the carpus were proposed. In 1896, Bryce compared the movements of his own wrist with that of prepared specimens using arthrograms. His work concluded that the centre of rotation of the joint must lie in the capitate, describing a screw-like motion of the lunate within the circumferential motion of the wrist. He noted that the motion of the scaphoid on the lunate occurred around the stronger dorsal component of the scapholunate interosseous ligament and that the hand pronated on the forearm in ulnar deviation and supinated in radial deviation (Dobyns and Linscheid, 1997). This description led other researchers to ponder the mechanics of the carpus. In 1904, Fisk used sections of geometric constructions to make a comparison between the motion of various types of carpal
joint surfaces (Dobyns and Linscheid, 1997). Fisk generated much interest, and pioneered a new descriptive model for the carpus, which combined classic anatomical descriptions with the motion of individual/groups of bones. In doing so, Fisk pioneered the development of the study into carpal kinematics and carpal kinetics.

The most common descriptive model is the division of the carpal bones into proximal and distal rows (Berger et al., 1982; Craigen and Stanley, 1995; Garcia-Elias, 2001). In this classic description, anatomists divided the carpus into two rows: a distal row consisting of the hamate, capitate, trapezium, and trapezoid; and a proximal row consisting of the triquetrum, pisiform and lunate, with the scaphoid bridging the two rows. The theory stated that flexion and extension occurred at the midcarpal joint and radial and ulnar inclination by the scaphoid sliding down the slope of the distal radius (Johnson, 1907). The proximal carpal row is an intercalated segment (Landsmeer, 1961; Linscheid et al., 1972a) whose direction of motion depends on the posture and movement of the distal carpal row, and whose stability and range depend on its ligamentous integrity and articular surface anatomy (Horii et al., 1993; Moojen et al., 2002b). In this description, the pisiform functions as a sesamoid, providing a lever arm for the flexor carpi ulnaris tendon (Burke, 1996; Garcia-Elias et al., 1996; Millender and Nalebuff, 1973; Moojen et al., 2001; Pevny et al., 1995). Accessory carpal bones exist in less than 2% of the population, the os centrale being one of the most common of the twenty different variants reported (Senecail et al., 2007). In practice this ossicle, located between the scaphoid, capitate, and trapezoid, has been implicated as an unusual cause of painful "clicking" of the wrist (Sacks, 1949).

Navarro (1921) originally proposed the column theory. In this theory, the carpal bones can be divided into three columns: the central, the lateral, and the medial columns. The central column consists of the lunate, capitate, and hamate; the lateral column of the scaphoid, trapezium, and trapezoid; and the medial column of the triquetrum and pisiform. Taleisnik (1976) modified this theory. He believed that the distal row effectively acted as a single unit with the lunate; with the lateral column formed solely by the scaphoid, and the medial column being formed by the triquetrum only. Both researchers believed that the central column controls wrist flexion and extension, with radial and ulnar inclination occurring by rotation of the scaphoid and triquetrum about the central axis.

These descriptive methods relate to theories based on the mechanics of the wrist. They have been used extensively to compare and contrast different theories of carpal mechanics (Craigen
and Stanley, 1995; Kauer and De Lange, 1987), and to aid in their explanation. Carpal kinematic theories have evolved to incorporate several theories in addition to those that support the column (Navarro, 1921b; Taleisnik, 1976) and row (von Bonin, 1929); that is, the intercalated segment (Landsmeer, 1961; Weber, 1984b) and oval ring concepts (Lichtman et al., 1981; Moritomo et al., 2006). Although there remains uncertainty and debate regarding the movements of the carpus, the collaborative understanding of the complex intercarpal motion that occurs with wrist motion has greatly advanced. This progress can be attributed largely to the multitude of in vitro (Berger et al., 1982; Garcia-Elias et al., 1989; Ruby et al., 1988) and in vivo studies (Moojen et al., 2003; Wolfe et al., 2000) that have laid the groundwork for progressing carpal kinematic understanding. This progression is supplemented by the development of noninvasive, markerless in vivo CT and MRI techniques for precisely measuring carpal mechanics. These newer techniques are still in their infancy, and have not yielded a unified theory on wrist motion (Gardner et al., 2006; Moritomo et al., 2004, 2006).

As collaborative research continues, important information on carpal motion in normal and pathologic states will inevitably be obtained. For the purposes of this thesis, the proximal and distal row descriptive terms have been used to describe the anatomical positions of the carpal bones. The motion at the wrist joint is complex and is beyond the scope of this thesis.

1.1.2.3 Carpal morphology

Much progress has been made regarding our understanding of carpal anatomy, carpal kinematics and carpal kinetics. However, the majority of descriptions and studies have been performed without consideration for the tremendous variation between individuals in regard to bone structure, ligamentous attachments and tendon attachments.

The orientation of the carpal bones is such that their irregular morphologies can be utilised to some mechanical advantage (Kauer, 1986). Their design is a compromise between motion and stability, allowing a unique combination of precise positioning and stability over a large range of motion (Berger, 1996; Bogumill, 1988; Kauer and De Lange, 1987; Lewis et al., 1970). Analysis of the wrist requires an understanding of the skeletal morphologies, and particularly how variations of these morphologies relate to variations in soft tissue orientation (Viegas, 2001b). Ultimately, understanding such variations will facilitate a clearer understanding of the function and dysfunction of the wrist. Although important, carpal ligament and tendon
morphology are complex subjects that are not the focus of this thesis. The osseous carpal morphological variants described in the literature are presented in detail.

Several morphological variants have been described at the wrist and are described in detail in Chapter 2. Viegas (1990) described two different types of lunate morphology. Taleisnik (1993) described two different patterns of morphology at the distal scaphoid, while Ceri et al. (2004) described two patterns of morphology related to the scaphoid waist. Yazaki et al. (2008) described three different types of capitate morphology. McLean et al. (2007) described two patterns of triquetral-hamate articulation with a spectrum of variation in-between. This description included two different types of triquetral morphology and two different types of hamate morphology.

Despite these descriptions, the associations between the various individual carpal morphologies have not been investigated. Specifically, the incidence of scaphoid, lunate, triquetral, hamate and capitate types has not been established. Additionally, the relationship between carpal morphology and carpal mechanics has not been investigated.
1.1.3 Imaging

1.2.3.1 Radiography

In 1895, Röntgen (Figure 1.7) developed the technique of radiology using x-rays, an achievement that earned him the first Nobel Prize in Physics in 1901. The first radiological image was of his wife’s hand (Figure 1.7-insert) with the characteristic omission of the wrist. Following this development, Röntgen presented his findings 50 days later in the original paper "On A New Kind Of Rays" (Über eine neue Art von Strahlen). Even over this short period, his technique had improved markedly to be capable of visualising characteristics of individual bones (Figure 1.8). As a consequence of his discovery, Röntgen is considered the father of diagnostic radiology.

Figure 1.7

In 1895, the German physicist Wilhelm C. Röntgen (1845-1923) discovered electromagnetic radiation in a wavelength range today known as x-rays. This achievement earned him the first Nobel Prize in Physics in 1901.

Insert: Wilhelm Röntgen's first "medical" x-ray, of his wife's hand, taken on 22 December 1895.
Over the next one hundred years, plain radiography has been the mainstay of imaging of the wrist, although interpretation has been challenging (Biondetti et al., 1987; Engdahl and Schacherer, 1989; Friedman et al., 1990). Advances in the methods, techniques and interpretation of radiological imaging of the wrist have been considerable. These have included different methods of performing the radiographs, including the development of specialised views to demonstrate the carpus (Berna et al., 1998; Berna et al., 1993; Gaebler et al., 1998; Proubasta et al., 1989).

1.2.3.2 Tomography

In the early 1900s, the Italian radiologist Alessandro Vallebona proposed a method to represent a single slice of the body on the radiographic film. This method was termed tomography (Filler, 2009). The idea was based on simple principles of projective geometry: moving synchronously and in opposite directions the X-ray tube and the film. Tomography had been one of the pillars of radiologic diagnostics until the late 1970s, when the availability of minicomputers and of the transverse axial scanning method, gradually supplanted it as the
modality of computed tomography (CT) (Filler, 2009). The first commercially viable CT scanner was invented by Sir Godfrey Hounsfield in Hayes, United Kingdom at EMI Central Research Laboratories using X-rays (Figure 1.9) (Filler, 2009). Allan McLeod Cormack of Tufts University in Massachusetts independently invented a similar process, and both Hounsfield and Cormack shared the 1979 Nobel Prize in Medicine for their discoveries (Filler, 2009). Clinical use of CT has evolved since this time to be the mainstream of clinical practice, especially in the evaluation and diagnosis of musculoskeletal disorders. It is now regarded as a standard requirement in pre-operative planning of osseous processes and a critical requirement in the comprehensive assessment of carpal disorders.

**Figure 1.9**

A picture of Sir Godfrey Hounsfield (28 Aug 1919 – 12 Aug, 2004) standing next to the computed tomography scanner he developed. He shared the 1979 Nobel Prize for Physiology or Medicine with Allan McLeod Cormack for his part in developing the diagnostic technique of X-ray computed tomography.

1.2.3.3 Three-dimensional computed tomography

2-dimensional (2-D) CT has evolved to incorporate more sophisticated methods of imaging, including 3-dimensional (3-D) CT. 2-D CT can now be used to create 3-D images using either surface-rendering or volume-rendering techniques (Harris et al., 1979). Surface-rendered CT images involve the production of a 3-D model, based on a threshold value of radiodensity that is chosen by the operator (e.g. a level that corresponds to bone) (Harris et al., 1979). A threshold level is set and from this, using edge detection image processing algorithms, a 3-D model can be constructed and displayed on a screen. Multiple models can be constructed from
various different thresholds, allowing different colours to represent each anatomical component such as bone, muscle, and cartilage (Harris et al., 1979). Volume-rendered 3-D CT images are limited in that this technique will only display surfaces that meet a threshold density, and will only display the surface that is closest to the imaginary viewer (Harris et al., 1979). In volume rendering, transparency and colours are used to allow a better representation of the volume to be shown in a single image – i.e. the bones of the carpus can be displayed as semi-transparent, so that even at an oblique angle, one part of the image does not conceal another. The clinical application of this minimally-invasive technology is vast, and has dramatically improved the amount of information available to surgeons when considering pre-operative planning. 3-D reconstructions are now used routinely in the evaluation and pre-operative planning of complex carpal injuries, including ligament disruptions and fractures.

1.2.3.4 Magnetic Resonance Imaging (MRI)

Nikola Tesla discovered the Rotating Magnetic Field in 1882 in Budapest, Hungary (Figure 1.10) (Hurwitz, 2000). In working with radio waves, Tesla created the Tesla coil as a means to generate and receive radio wave energy. This was a fundamental discovery in physics. Following on from this, in 1937 Isidor Rabi observed the quantum phenomenon, dubbed ‘nuclear magnetic resonance’ (NMR) (Hurwitz, 2000). He recognized that the atomic nuclei show their presence by absorbing or emitting radio waves when exposed to a sufficiently strong magnetic field, a finding for which he received the 1944 Nobel Prize in physics. Following this discovery, Felix Bloch of Stanford University and Edward Purcell of Harvard University, working independently, made the first successful NMR experiments to study chemical compounds in 1946 (Ranck, 2008). For their findings, Bloch and Purcell were awarded the Nobel Prize for Physics in 1952. In 1971, Raymond Damadian discovered that the hydrogen signal in cancerous tissue was different from that of healthy tissue (Ranck, 2008). When the magnetic resonance imaging (MRI) machine was switched off, the bath of radio waves from cancerous tissue lingered longer then those from the healthy tissue. This fundamental discovery led Paul Lauterbur in 1973 to produce the first NMR image (Ranck, 2008). However, it was not until 1977 that the first human scan was made using the first MRI prototype.

Since this time, MRI has evolved to become a standard method of imaging the internal structures, especially those structures with high water or fat content, including cartilage, ligaments, tendons, muscles and bones. As such, its application in the evaluation of the
muskuloskeletal system is vast. The clinical applications of this minimally-invasive technology has dramatically improved the amount of information available to surgeons when considering pre-operative planning. MRI is now used routinely in the assessment and management of a range of carpal disorders involving cartilage, ligaments, tendons, muscles and bones.

1.2.3.5 Arthrography

Shortly after the advent of x-rays, arthrography was introduced for the evaluation of joint pathology (Werndorff and Robinson, 1905). The first techniques used air and early iodinated contrast agents (Figure 1.11). However, arthrography did not really flourish until the mid portion of the last century when better-tolerated water-soluble iodinated contrast media became more readily available (Peterson et al., 2008). Arthrography saw its widest use in the 1960s and 1970s, but indications for many joints decreased significantly after the introduction of cross-sectional imaging modalities such as CT and MR imaging (Peterson et al., 2008). The use of arthrography has grown again with the introduction of CT and MR arthrographic techniques, which were introduced the 1980s and continue to be refined.

Figure 1.10

A photograph of Nikola Tesla (1856-1943) was an inventor and a mechanical and electrical engineer. He was credited with many revolutionary contributions to the field of electricity and magnetism in the late 19th and early 20th centuries. Tesla's patents and theoretical work formed the basis of electromagnetism, modern alternating current electricity (AC) systems, including the polyphase power distribution systems and the AC motor, with which he helped usher in the Second Industrial Revolution.
Wrist arthrography was first reported in 1961 by Kessler and Silberman (1961), who described radiocarpal- joint injections in patients, who had ‘‘injuries of the wrist with negative roentgen-ray examinations.’’ This work demonstrated that intra-articular administration of contrast medium contrast into the radiocarpal joint allowed visualization of triangular fibrocartilage complex (TFCC) defects that were undetectable by conventional radiography. Arthrography delineated communication of the radiocarpal articulation and the distal radioulnar joint (DRUJ) with spillage of contrast medium through the torn TFCC (Kessler and Silberman, 1961). In modern practice, CT arthrography is an alternate way of imaging the internal structure of joints, including the cartilage, ligaments, joint lining and the structures around the joint, including the tendons, muscles and bones. The clinical application of this minimally-invasive technology is vast, and has improved the amount of information available to surgeons when considering pre-operative planning. Although not discussed in detail in this thesis, arthrography of the wrist has been used in the evaluation and pre-operative planning of complex carpal injuries including ligament disruptions and TFCC tears (Brown et al., 1994; Kessler and Silberman, 1961). However, it is not used widely in clinical practice because studies have demonstrated that perforations of the TFCC are a common, normal wrist variant.

Figure 1.11
Radiocarpal-joint injection. First described by Kessler and Silberman (1961), radiocarpal-joint injections can evaluate both the TFCC and the scapholunate and lunotriquetral ligaments. In this case, all are intact, with contrast medium maintained within the radiocarpal articulation and no abnormal communication with the adjacent joint compartments.
1.1.4 Modern carpal functional anatomy

As visualisation of all of the structures of the carpus during surgery is impossible and impractical, surgeons primarily base their understanding of carpal anatomy on cadaveric investigations. However, many of the carpal ligaments and osseous features cannot be visualised without the extrinsic ligaments and tendons being incised and removed (Figure 1.12). This limits the scope of these investigations, as many of the anatomic and mechanical properties of the structures being investigated are compromised. Consequently, a thorough understanding of carpal anatomy has relied on the correlation of the progressive cumulative understanding of classical anatomists, arthroscopists and various imaging modalities. Indeed, as advances in investigational technologies have been developed, the embracement of these research tools has led to a progressively greater understanding of the carpus. Correspondingly, as more detailed imaging modalities become available, a more detailed understanding of anatomy will develop (Berger, 1999; Bettinger et al., 1995; Whipple, 1992). Despite the slow initial development, there have been exponential advances in the understanding of the normal and abnormal wrist in the areas of anatomy, imaging and surgery particularly in the last 20 years. Advances in one area often provide the basis for development in another area.

There has been a progressive advance of our understanding of wrist anatomy. These developments include an improved understanding of wrist morphology (Kauer, 1986; Viegas, 1990b; Viegas et al., 1993a; Weber, 1984a), kinematics (Craigen and Stanley, 1995; Garcia-Elias et al., 1995; Landsmeer, 1961; Lichtman et al., 1981; Moritomo et al., 2006; Morrey and An, 1985; Navarro, 1921a; Taleisnik, 1976; von Bonin, 1929) and carpal instability (Linscheid et al., 1972b; Mayfield et al., 1980). This knowledge interfaces with imaging and surgery for the wrist.

There remains considerable opportunity to further develop our knowledge of anatomy and imaging and to transfer this into the clinical and surgical practice in a safe and efficient manner.
Figure 1.12

The extrinsic volar carpal ligaments of the wrist. (From - Berger, 1996).


Bones: R: radius; U: ulna; S: scaphoid; L: lunate; T: triquetrum; P: pisiform; Tm: trapezium; Td: trapezoid; C: capitate; H: hamate.
1.2 Aims of thesis.

1. To increase our understanding of the wrist.
2. To investigate potential association(s) between osseous morphology and pathology of the carpus.

1.3 Significance of aims.

To develop the understanding of the wrist is important, as improved knowledge will facilitate a clearer understanding of the function and dysfunction of the wrist, and aid in the formulation of efficacious treatment plans that are anatomically and mechanically sound (Berger, 2001; Garcia-Elias et al., 1989). Analysis of the wrist requires an understanding of the skeletal morphologies, and particularly how variations of these morphologies relate to variations in soft tissue orientation (Viegas, 2001b). Before attempting to understand the intricacies of carpal mechanics and pathomechanics, it is important that a surgeon have a thorough grasp of carpal anatomy.

Having built these fundamental anatomical principles, the clinician can apply them when assessing clinical and radiological aspects of the abnormal wrist. The surgeon aims to improve a patient’s symptoms by establishing a diagnosis before embarking on a treatment plan. To achieve this, a surgeon must have a comprehensive knowledge of the normal and abnormal wrist. As such, it is important that potential association(s) between different osseous morphologies and pathologies of the carpus be investigated and understood. This improves the collective knowledge of the wrist, allowing more detailed, clinically relevant information can be obtained and applied for each individual patient.

1.4 Objectives of thesis

1. To develop an understanding of the morphological variants of the normal wrist, including:
   a. morphology of the capitate;
   b. morphology of the hamate;
   c. morphology of the scaphoid;
   d. morphology of the lunate; and
   e. morphology of the triquetrum.
2. To develop an understanding of the non-invasive imaging modalities available for the assessment of disorders of the:
   a. capitate;
   b. hamate;
   c. lunate;
   d. scaphoid; and
   e. triquetrum.

3. To develop an understanding of the associations between morphology and disease processes, specifically:
   a. osteoarthritis; and
   b. carpal instability.

4. To develop an understanding of the classification of complex carpal injuries, including:
   a. carpal fractures;
   b. carpal instability; and
   c. combined carpal fractures with carpal instability.
Chapter 2 - LITERATURE REVIEW

2.1 Anatomy

2.1.1 Introduction

The anatomy of the wrist is outlined, with specific reference to the morphological variants described in the literature. The rationale for further studies is presented. The studies performed in this thesis seek to address these deficiencies.

2.1.2 Capitate morphology

The capitate is the largest of the carpal bones, and occupies much of the centre of the carpus, with its centre of ossification becoming evident during the first months of life (Kohler and Zimmer, 1968). The capitate can be divided into head, neck and body (Berger, 1996). The head is the hemispherical proximal aspect of the capitate (Bogumill, 1988), and is purely articular, receiving no ligamentous attachments (Berger, 1996). It articulates with the concave distal aspect of the lunate and the concave facet on the ulnar aspect of the scaphoid. The curvature of the proximal head of the capitate at the midcarpal joint is highly variable (Peh and Gilula, 1996; Pfirrmann et al., 2002), with a correspondingly shallow or deep scaphoid facet (Kauer, 1986). A smaller diameter of curvature of the proximal head of the capitate has been found to be associated with wrists with a lunate facet for the hamate (Nakamura et al., 2000; Pfirrmann et al., 2002). Normally, there is an associated ridging on the capitate that corresponds to the recess of the scapholunate joint.

Distal to the head of the capitate is a narrow neck, lined with periosteum, which represents the transition between the head and the body. The remaining region of the capitate distal to the neck is termed the body. The dorsal and volar aspects of the body are predominately covered with ligamentous attachments (Berger, 1997; Bogumill, 1988; Feipel and Rooze, 1999a; Taleisnik, 1976). The volar trapezoid-capitate ligament, dorsal trapezoid-capitate ligament, volar capitate-hamate ligament, dorsal capitate-hamate ligament, radioscapohamate ligament, scaphocapitate ligament, triquetrum-capitate ligament, ulnocapitate ligament and the capitate-metacarpal ligaments are attached to the body of the capitate (Berger, 1996). The volar aspect may have part of the adductor pollicis muscle variably insert into it (Bogumill, 1988).
On the ulnar side of its body, the capitate articulates with the hamate via a flat, elongated facet (Bogumill, 1988). On the radial side, it articulates with the trapezoid. The articular surfaces of these two joints are interrupted by the notched attachment sites (Berger, 2001) for the deep trapezoid-capitate and capitate-hamate ligaments (Berger, 1996).

Yazaki et al. (2007) recently described three types of capitate based on the articulating surface of the capitate head, as alluded to by Viegas (1990a) (Figure 2.1). In this description, a Flat Type (F-Type) capitate was characterized by a horizontal lunate articulation and a nearly vertical scaphoid articulation. A V-Shaped Type (V-Type) capitate had separate lunate and scaphoid facets that converge, and were separated by a visible ridge (capitate ridge), corresponding to the direction of the triquetral-lunate joint. A Spherical Type (S-Type) capitate had an associated concave articulation formed by the scaphoid and lunate facets. The capitate head corresponded to the shape of the capitate facet of the scaphoid. Variations in the concavity of the scaphoid facet for the capitate have been identified (Compson et al., 1994; Garcia-Elias, 2001), with the facet ranging from shallow, to deeply convex (Burgess, 1990; Compson et al., 1994; Dyankova, 2007; Fogg, 2004; Garcia-Elias, 2001; Kauer, 1986; Nakamura et al., 2000). It has been suggested that differences in capitate type are likely to be associated with variations in ligament composition and distribution, differences in carpal kinematics and pathomechanics, and variations in surgical outcomes (such as proximal row carpectomy) (Yazaki et al., 2007).

No literature exists on the best methods for differentiating capitate type using imaging techniques. Furthermore, no literature exists comparing capitate type with ligament composition and distribution, carpal kinematics and pathomechanics, or surgical outcomes.
Figure 2.1

Dissected specimens of the midcarpal joint opened dorsally. C: capitate; H: hamate; L: lunate; S: scaphoid; T: triquetrum. From Yazaki et al. (2009).

A. A flat type (F-type) capitate, characterized by a horizontal lunate articulation and a nearly vertical scaphoid articulation.

B. A V-shaped (V-type) capitate, characterized by separate lunate and scaphoid facets that converge, separated by a visible ridge, corresponding to the direction of the scapholunate joint.

C. A spherical (S-type) capitate, characterized by a round capitate head, with an associated concave articulation formed by the scaphoid and lunate facets.
2.1.3 Hamate morphology

The hamate (os hamatum), or unciform bone, derives its name from the Latin *hamatus* "hooked," from *hamus* which means "hook". It occupies the ulnar border of the distal row of the carpus; becoming ossified during the first year of age (Kohler and Zimmer, 1968). The hamate is wedge-shaped, with a hook-like process that projects volarly (Schaeffer, 1953). The wedge projects from its base proximally, with its apex directed volarly and radially. The hamate is bordered proximally by the pisiform and lunate in the proximal carpal row, radially by the capitate, and distally by the bases of the fourth and fifth metacarpals (Davies, 1967).

The hamate is divided into proximal pole, hook and body regions. The proximal pole is articular, with a flat and elongated radial facet for articulation with the capitate (Bogumill, 1988), and an ulnar facet for articulation with the triquetrum. Ulnarly, the triquetrum-hamate joint has been described as a saddle-joint (Johnson, 1907), as helicoidal (Weber, 1984b) or as screw-shaped (Kauer, 1986; McConaill, 1941). McLean et al. (2006) described two distinct patterns of triquetral-hamate articular joints, with a spectrum of variation in-between (Figures 2.2, 2.3, 2.5 and 2.6). In this study, two distinct patterns of hamate joint surface surface were identified. At one end of the spectrum, the hamate possessed a prominent groove that formed a ridge distally. This configuration formed a helicoidal TqH joint composed of double-faceted, complementary concave and convex parts (McLean et al., 2006). At the other end of the spectrum, the hamate possessed no hamate groove or distal ridge, and it formed a joint that was predominantly oval convex (McLean et al., 2006).

The apex of the wedge variably articulates with the lunate (Berger, 1996; Burgess, 1990; Viegas et al., 1990). In wrists, in which the hamate articulates with the lunate, the triquetrum-hamate joint surface is divided from lunate-hamate articulating surface by a visible ridge, corresponding to the luno-triquetral joint (Burgess, 1990; McLean et al., 2006; Viegas et al., 1990) (Figure 2.4). This ridge is absent in wrists, in which the hamate does not articulate with the lunate (McLean et al., 2006).

The hamate body may be divided into volar and dorsal surfaces. The dorsal surface is triangular and rough for ligamentous attachment. The volar surface presents the hook of hamate, which is completely covered with ligamentous attachments, including the flexor retinaculum and the pisohamate ligament. Ligaments attaching to the body include the volar and dorsal capito-hamate ligaments, the deep capito-hamate, the volar and dorsal hamate-
metacarpal ligament and the triquetral-hamate ligaments. The hook of hamate forms the lateral (radial) border of Tunnel of Guyon, which transports ulnar nerve and artery to the hand. In practice, a hook of hamate fracture can be associated with ulnar artery and/or nerve damage, as the canal carries the ulnar artery and nerve. In addition, the hook of hamate has a dual blood supply, with vessels entering from both the ulnar tip and radial base. These vessels often have a poor anastomosis, which clinically can result in non-union of hamate hook fractures due to insufficient blood supply (Failla, 1993).

**Figure 2.2**

Figure 2.3

A proximal view of the hamate (looking from the ulnar side of the right hand toward the digits). A. A spiral-type hamate showing the hamate groove (HG) and distal ridge (DR). B. A flat-type hamate with no distal ridge or hamate groove. HH: hook of hamate; PAS: proximal articulating surface. From – McLean et al. (2006).

Figure 2.4

The proximal aspect of the capitate (C) and the hamate (H) showing the ridge (double arrow) on the hamate that corresponded to the recess of the lunotriquetral joint and a ridge (one arrow) on the capitate that corresponded to the recess of the scapholunate joint. From - Viegas et al. (1990a).
It has been suggested that differences in hamate type are likely to be associated with variations in carpal kinematics patterns and pathomechanics (Yazaki et al., 2007). However, further studies are needed to test this theory. Currently, there is little in the current literature to address non-invasive imaging identification of hamate morphology, and no standard exists for accurate recognition of the variants by different imaging techniques. This has limited the development in understanding carpal kinematics and pathomechanics and any differences that might be related to these variations in hamate morphologic features. In addition, no literature exists comparing hamate type with ligament composition and distribution, carpal kinematics and pathomechanics, or surgical outcomes.
Figure 2.5

The dorsoulnar aspect of the hamate (looking toward the center of the palm from the lateral side of where the extensor carpi ulnaris traverses over the carpal bones). **A.** A type I hamate showing the hamate groove (HG) and distal ridge (DR). **B.** A type II hamate with no distal ridge. There is a hamate ridge (HR) on the proximal articulating surface, which signifies that this hamate articulates with a type 2 lunate. From – McLean et al. (2006).

Figure 2.6

A dorsal view of **A.** a spiral-type hamate and **B.** a flat-type hamate (looking from the dorsum of the wrist to the hypothenar eminence). DR: distal ridge; HG: hamate groove; PAS: proximal articulating surface. Compared with the spiral-type hamate (A), there is no distal ridge or hamate groove, in a flat-type hamate, as shown in B. From – McLean et al. (2006).

NOTE:
This figure is included on page 30 of the print copy of the thesis held in the University of Adelaide Library.
2.1.4 Scaphoid morphology

A comprehensive synopsis of scaphoid morphology is presented in Chapter 3.

The distal articular surface of the scaphoid has been reported to have a variable inter-facet ridge that divides the surface into two articular facets (Berger, 1997; Compson et al., 1994; Kauer, 1986; Moritomo et al., 2000c; Nuttall et al., 1998; Taleisnik, 1985), corresponding to the direction of trapezio-trapezoidal (TT) articulation. Moritomo et al. (2000a) has suggested that the presence or absence of this ridge may indicate a clear pattern of scaphoid motion, relative to the TT joint. There has been no report of radiographic recognition of the scaphoid ridge, nor has the ridge been investigated to compare STT in-joint loading, pathomechanical processes, or injury patterns.

2.1.5 Lunate morphology

The lunate has been described as the “keystone” in the proximal carpal row when wrist stability is considered (Sennwald et al., 1993). Variations in lunate ossification have been reported, including ossification onset (Poznanski, 1984; Wetherington, 1961), double ossification centres (Eggimann, 1951; Wetherington, 1961), total lunate absence (Kobayashi et al., 1991; Postacchini and Ippoplito, 1975; Roche, 1967), and various congenital fusions, including the relatively common lunotriquetral coalition (Carlson, 1981; Cope, 1974; O’Rahilly, 1953, 1957; Senecail et al., 2007). Additionally, ossification may be delayed in individuals with various syndromes including epiphyseal dysplasias and homocystinuria (Morreels et al., 1968; Tamburrini et al., 1984).

The lunate, so named because of its crescent-shape reminiscent of a crescent moon (Davies, 1967), lies central in the proximal row of the carpus. The lateral and medial surfaces are small and flat surfaces, for articulation with the scaphoid and the triquetrum respectively (Berger, 1996; Bogumill, 1988). The lunate is divided into volar and dorsal poles (Berger, 1996), of which the dorsal pole is smaller, thus giving the lunate a wedge shape (Gupta and Al-Moosawi, 2002). The lunate is not only wedge-shaped in the sagittal plane with its apex dorsally, but in the coronal plane also, with a laterally displaced apex (Gupta and Al-Moosawi, 2002).
Figure 2.7

The proximal aspect of the midcarpal joint showing a Type I lunate that does not have a medial hamate facet. (S: scaphoid; L: lunate; T: triquetrum). From – Viegas, 2001.

Figure 2.8

The proximal aspect of the capitate and the hamate showing the cartilage erosion with exposed subchondral bone that often was seen associated with the Type II lunate. Note the large radial sided facet of the lunate (L) and small ulnar sided facet of the lunate (arrow). The hamate (H) articulates with the ulnar facet of the lunate and the triquetrum (T). The capitate (C) articulates with the scaphoid and the radial facet of the lunate. From – Viegas et al., 1990.
The lunate has previously been classified into three types (D, V, or N) based on the measurements of the comparative heights of the lunate’s volar and dorsal segments (Watson et al., 1996). However, subsequent studies using CT sagittal images of individual lunates very often did not demonstrate shape of a similar type, but showed a mixed pattern with two or even three type of shapes in the same lunate (Gupta and Al-Moosawi, 2002).

At the radiocarpal joint, the proximal margin of the lunate articulates with the shallow lunate fossae (Boabighi et al., 1993; Bogumill, 1988; Berger and Garcia-Elias, 1991; Boabighi et al., 1988; Garcia-Elias and Lluch, 2001). At the midcarpal joint, the lunate is concave in the coronal and sagittal planes. The distal aspect of the lunate articulates with the capitate, and variably with the hamate (Berger, 1996; Burgess, 1990; Viegas et al., 1990). Two distinct types of lunate have been described (Burgess, 1990; Viegas, 1990a; Viegas et al., 1993c; Viegas et al., 1990), with a spectrum of variation in between (Galley et al., 2007; Nakamura et al., 1997; Pfirrmann et al., 2002).

Viegas (1990) categorized two types of lunate, based on the midcarpal distal articulation of the lunate, as alluded to by Burgess (1990). In this description, a type 1 lunate has a single distal facet for the capitate, and does not articulate with the hamate (Figure 2.7). In contrast, a type 2 lunate has two distal facets; the radial facet articulates with the capitate, and the ulnar facet articulates with the hamate (Figure 2.8). The reported incidence of the type 1 ranges from 27% to 35% and type 2 from 66% to 73% (Burgess, 1990; Kaempffe and Lerner, 1996; Viegas, 1990a; Viegas et al., 1993a; Viegas et al., 1993b). The type of lunate can usually be determined based on plain radiographs (Figures 2.9 and 2.10), although a small facet may be difficult to identify (Sagerman et al., 1995b). Differences in lunate type have been reported to be associated with variations in ligament composition and distribution (Viegas, 2001a, 2001b; Viegas et al., 1993c; Viegas et al., 1993d), carpal kinematics (Galley et al., 2007; Nakamura et al., 2000) and pathomechanics (Haase et al., 2007), and various carpal pathologies (Nakamura et al., 2001; Pfirrmann et al., 2002; Sagerman et al., 1995a; Viegas, 1990a, 2001b; Viegas et al., 1993c). Several reports indicate that a reliable diagnosis of this anatomic variant and, more importantly, the associated chondral lesions, requires midcarpal arthroscopy (Sagerman et al., 1995a; Viegas, 1990a, 1994).
Figure 2.9
Type 1 lunate. A wrist radiograph of a type 1 lunate, with a single distal facet for the capitate; it does not articulate with the hamate. From – Galley et al (2007).

Figure 2.10
Type 2 lunate. A wrist radiograph of a type 2 lunate, with two distal facets; the radial facet articulates with the capitate, and the ulnar facet articulates with the hamate. From – Galley et al (2007).
2.1.6 Triquetrum morphology

The triquetrum is a small, irregularly-shaped bone that occupies the ulnar-most position in the proximal row of the carpus. The proximal articular surface is convex and usually articulates with the triangular fibrocartilage complex (TFCC) of the wrist (Berger, 1996). Radially, the triquetrum has a flat quadrilateral facet for articulation with the lunate. Distally, the triquetrum articulates with the hamate. The variability of the triquetral-hamate (TqH) joint has been well-documented. The articulation between the triquetrum and the hamate has been described as saddle-shaped (Johnson, 1907; Kauer, 1986), helicoidal (Weber, 1984b), screw-shaped (McConaill, 1941; Weber, 1984b), ovoid (Moritomo et al., 2003; Moritomo et al., 2006), and cup-shaped (Burgess, 1990). McLean et al. (2006) described two distinct patterns of TqH articular joints, with a spectrum of variation in-between (Table 2.1, and Figure 2.11). One joint type was a helicoidal configuration, with double-faceted, complementary concave and convex parts; the other was predominantly oval convex, where the primarily concave triquetrum was described as a “dish” for the flatter hamate (Figure 2.2).

It has been suggested that differences in triquetral type are likely to be associated with variations in carpal kinematics patterns and pathomechanics, in a similar manner to the hamate (Yazaki et al., 2007). However, further studies are needed to test this theory. Currently, there is little in the literature to address non-invasive imaging identification of triquetral morphology, and no standard exists for accurate recognition of the variants by different imaging techniques. This has limited the development in understanding of carpal kinematics and pathomechanics and any differences that might be related to these variations in triquetral morphologic features. In addition, no literature exists comparing triquetral type with ligament composition and distribution, carpal kinematics and pathomechanics, or surgical outcomes.
Figure 2.11

The triquetro-hamate articulating surface of a helicoidal (A) and a flat triquetrum (B).

A. A helicoidal triquetrum has a broad proximal joint surface and narrow distal joint surface. This forms a helicoidal joint configuration with the hamate, with double-faceted, complementary concave and convex parts. B. In contrast, in a flat triquetrum, the joint surface remains broad distally and is almost flat. This forms a predominantly oval convex joint configuration with the hamate, where the primarily concave triquetrum is described as a “dish” for the flatter hamate.
2.2 Carpal pathology

2.2.1 Introduction

A detailed description of all carpal pathologies is beyond the scope of this thesis. The conditions presented have been found to have associations that vary between different wrist morphologies. These findings raise the possibility that carpal pathomechanics are integrally related to wrist morphology. Before attempting to understand the intricacies of carpal surgical management, it is important that a surgeon have a thorough understanding of the skeletal morphologies, and particularly how variations of these morphologies may relate to variations in soft tissue orientation, carpal pathomechanics and carpal kinematics (Viegas, 2001b). Ultimately, understanding such variations will facilitate a clearer understanding of the function and dysfunction of the wrist, and aid in the formulation of efficacious treatment plans that are anatomically and mechanically sound (Berger, 2001; Garcia-Elias et al., 1989).

2.2.2 Osteoarthritis

Viegas et al. (1993) reported that the incidence of midcarpal osteoarthritis (OA) at the lunate-hamate joint was largely confined to type 2 lunate wrists, suggesting that wrist morphology was a determinant in the development of midcarpal OA (Viegas et al., 1993) (Figure 2.12). Several investigators have suggested that variations in morphology contribute to differences in carpal kinetics, joint loading and soft tissue constraints, which influence the patterns of OA seen at the wrist (Haase et al., 2007; Nakamura et al., 2001; Viegas, 2001b).

The shape of the lunate influences the movement of the scaphoid, during ulnar and radial deviation (Galley et al., 2007; Nakamura et al., 2000). As motion at the scapho-trapezio-trapezoidal (STT) joint is closely related to scaphoid kinematics, it is possible that variations in lunate morphology may be related to the pathogenesis of STT OA. However, STT OA has not been correlated with morphology.
2.2.3 Carpal instability

Recent literature has reported an association between carpal morphology and carpal instability (Haase et al., 2007). Haase et al. (2007) reported that type 2 lunate morphology was associated with a decreased incidence of dorsal intercalated segment instability (DISI) deformity in cases of established scaphoid non-union. Scaphoid non-union is a condition well known to predispose to carpal instability, specifically DISI deformity. Haase et al. (2007) theorized that a type 2 lunate’s articulation with the hamate lends some additional stability that resists abnormal extension and that type 2 lunate morphology is protective against DISI deformity in this clinical setting. Haase et al. (2007) suggested that the triquetrum’s usual “extension moment,” caused by force transmitted through its screw-like articulation with the hamate, was halted by the lunatohamate articulation present in type II midcarpal joints.

As a consequence of this finding, the available literature on lunate fractures was reviewed (Noble and Lamb (1979); Mason (1986); Teisen and Hjarbaek (1988); Sasaki (1991); Takase

Figure 2.12

The proximal aspect of the capitate (C) and the hamate (H) showing the cartilage erosion with exposed subchondral bone that often was seen associated with the type 2 lunate. From – Viegas et al. (1990).
(2006)), in an attempt to determine whether the same principle applied to trans-lunate fractures. However, no literature that addressed the potential association(s) between carpal morphology and trans-lunate fractures was identified.

What was indentified, was that isolated fractures of the lunate are rare (Kuderna, 1986; Razemon, 1988; Teisen and Hjarbaek, 1988) and that these trans-lunate fractures were commonly associated with a combination of co-incident ligament ruptures and other carpal fractures. In addition, the combined, rare condition of trans-lunate, peri-lunate fracture-dislocation are not included in the instability patterns as described by Johnson (1980) or Mayfield (1984) (Figures 2.13 and 2.14, respectively).
Figure 2.14

Mayfield’s 4 stages of perilunate instability. Stage I is disruption of the scapho-lunate ligament. Stage II is dislocation (usually dorsal) of the capitolunate articulation. Stage III is disruption of the luno-triquetral ligament. Stage IV involves tearing of the dorsal radiocarpal ligaments. From Mayfield (1984).

Figure 2.13

Johnson’s classification of perilunate instabilities. Greater arc (GA) injuries occur through osseous structures surrounding the lunate, such as the radial styloid, scaphoid, capitate, hamate, and triquetrum. Lesser arc (LA) injuries occur through the direct ligamentous structures surrounding the lunate, including the lunotriquetral and scapholunate ligaments.
2.3 Knowledge deficiencies

2.3.1 Scaphoid anatomy

The association between the scaphoid kinematics and morphology of the mid-carpal joint is unknown. Despite significant advances in the understanding of the scaphoid, there is not a single text or paper that presents this accumulated knowledge.

2.3.2 Imaging

It is not known if the various midcarpal morphologies can be identified using non-invasive imaging techniques.

The best method for non-invasive imaging identification of scapoid, lunate, hamate and capitate types has not been established.

The accuracy of imaging methods using plain AP radiographs, 2-D CT, 3-D CT and MRI for the identification of midcarpal morphological variants has not been established. No inter-observer variability study of the assessment of morphology using imaging techniques has been performed.

2.3.3 Midcarpal osteoarthritis

It is not known if an association exists between lunate morphology and midcarpal STT osteoarthritis.

2.3.4 Carpal instability

The current classification systems for the management of complex carpal injuries do not include all forms of the patterns seen in clinical practice.

The difficulties in assessment and management of complex carpal injuries have not been defined.
2.4 Relationship of the literature to the experimental program.

2.4.1 Scaphoid anatomy

The aims of the book chapter (Appendix 1) have been established to address the knowledge deficiencies in the literature in regard to scaphoid anatomy. This includes a comparison of the cumulative understanding of classical anatomists, arthroscopists and various imaging modalities, with regard to the scaphoid. The surface anatomy, osteology, ligamentous constraints, vascularity and its articulating joints are considered with respect to the current literature.

The literature review was the platform from which the studies were developed. It identified areas of future research, especially in relation to the potential associations between different scaphoid morphologies and various carpal pathomechanical processes.

2.4.2 Imaging

The aims of the experimental program have been established to address the knowledge deficiencies in the literature, including establishing the best method for non-invasive imaging identification of scaphoid, lunate, hamate and capitate morphological types. The paper was established because no clear standard existed for the non-invasive recognition of these morphological variants. The discussion of the paper addressed the relationship of the findings to the previous literature.

2.4.3 Midcarpal osteoarthritis

The aims of the experimental program have been established to address the knowledge deficiencies in the literature, including the potential association between lunate morphology and midcarpal STT OA. The discussion of the paper addressed the relationship of the findings to the previous literature.

2.4.4 Carpal instability

The aims of the paper were established to fill the knowledge deficiencies in the literature, including the current classification systems for the management of complex carpal injuries. The paper on carpal instability was written because of concerns about the current widely-
accepted complex carpal injury classification systems not inclusive of some cases experienced in clinical practice. The discussion of the paper addressed the relationship of the findings to the previous literature. Other objectives were related to established principles in the literature such as the diagnosis, management and prognosis of complex carpal injuries.

2.4.5 Research design

The experimental program designs were based on those already established in the literature.

2.4.6 Methodology

The subjective, objective and radiological measures of morphology were based on those already described in the literature.

The determination of safety and efficiency included comparing results to previously published works.
Chapter 3 – LITERATURE REVIEW – ANATOMY

3.1 Introduction

The book chapter presents a review of scaphoid anatomy from a surgical perspective. The relevant surface anatomy, osteology, ligamentous constraints, vascularity and articulating joints are discussed. The common pathomechanical processes are presented and their clinical implications discussed.

3.2 Book chapter title

Scaphoid anatomy (Appendix 1)

3.3 Chapter aims

1. To present a comprehensive synopsis of the cumulative understanding of classical anatomists, arthroscopists and various imaging modalities, with regard to the scaphoid.
2. To present the clinical implications of these advances in understanding.
3. To outline specific surgical considerations that need to be addressed when planning surgery to the scaphoid.

3.4 Chapter objectives

To present the current understanding of the scaphoid in regard to:

1. surface anatomy;
2. osteology;
3. ligamentous constraints;
4. vascularity; and
5. articulating joints.

To present the influence that carpal morphology has on carpal kinematics, with regard to the scaphoid.
To present the clinical implications of different scaphoid types, in regard to:

1. scaphoid kinematics;
2. scapholunate instability
3. scaphoid-trapezium-trapezoid arthritis

To outline the management principles for common scaphoid conditions.
Chapter 4 – COMPARISON OF IMAGING TECHNIQUES

4.1 Introduction

This research investigated the various imaging method(s) for identifying the various morphological variations at the midcarpal joint. The paper is discussed, with the research aims and objectives of the study being outlined. It includes the principles of study methodology and the main findings of the published research. It is not a restating of the published paper.

4.2 Paper title

Imaging Recognition of the Morphological Variants at the Midcarpal Joint (Appendix 2)

4.3 Research aims

To assess the best non-invasive imaging method for identifying midcarpal morphological variations at the wrist. The articular surfaces under investigation included the distal scaphoid, the distal lunate, the triquetral hamate opposing surfaces, and the proximal capitate.

4.4 Research objectives

1. To present the parameters that define the scaphoid, lunate, capitate, and hamate types, in respect to:
   1. scaphoid type, as described by Moritomo et al. (2000c)
   2. lunate type, as described by Viegas et al. (1990)
   3. hamate type, as described by McLean et al. (2006)
   4. capitate type, as described by Yazaki et al. (2008)

2. To identify which morphological parameters are identifiable, using:
   1. plain neutral antero-posterior (AP) radiographs
   2. 2-dimensional (2-D) computed tomography (CT)
   3. 3-dimentional (3-D) CT
   4. 3-tesla magnetic resonance imaging (MRI)
3. To definitively determine the midcarpal morphological variant for each wrist under investigation by dissection.

4. To compare the accuracy of imaging methods for identifying scaphoid, lunate, hamate and capitate types, using:

1. plain AP radiographs
2. 2-D CT
3. 3-D CT
4. 3-tesla MRI

5. To compare intra-observer and inter-observer agreement for categorization of carpal type for each imaging modality.

6. To determine the best non-invasive imaging method for identifying scapoid, lunate, hamate and capitate types, respectively.

4.5 Research performed

Thirteen unilateral adult human wrists were assessed by:

1. plain neutral AP radiographs
2. 2-D CT
3. 3-D CT
4. 3-tesla MRI
5. Dissection

Carpal measurements were performed, and the parameters that defined the scaphoid, lunate, hamate, and capitate morphological types were investigated, with dissection being used as the definitive measure of morphology.

The incidence of osteoarthritis was reported for the results of dissection.

The dissection findings were compared to the results of each imaging technique to determine the accuracy of morphological determination from each technique. Inter-observer and intra-observer agreement studies were performed according to the methods of Bland and Altman (1999) and Landis and Koch (1977). Correlation coefficients, sensitivity, specificity, positive
predictive value, negative predictive value, and accuracy were determined.

4.6 Main findings of the published research

Dissection could routinely determine morphological type, and was used as the definitive measure of morphology.

Imaging modalities:

1. Plain neutral AP radiographs could not routinely differentiate scaphoid, hamate or capitate types. Lunates with a large single or double facet could be routinely identified by plain AP radiographs. However, lunates with a small cartilaginous ulnar facet could not be accurately differentiated by plain AP radiographs. Lunates with small, cartilaginous facets were only identifiable with either coronal MRI or at dissection.

2. 2-D CT was not useful in the sagittal or axial planes. Coronal 2-D CT could not routinely differentiate scaphoid, hamate or capitate types. Lunates with a large single or double facets could be routinely identified by coronal 2-D CT. However, similar to plain neutral AP radiographs, lunates with a small cartilaginous ulnar facet could not be accurately differentiated by coronal 2-D CT.

3. 3-D CT could not routinely differentiate scaphoid, lunate or capitate types. Relatively accurate interpretation of hamate type was possible using 3-D CT. Using mathematical disarticulation of the triquetrum from the hamate, the surface of the hamate could be moved in 3-dimensions and visualized in any plane, and the presence or absence of the distal ridge could be thoroughly examined.

4. MRI could not determine hamate type. MRI in the transverse or sagittal planes could not routinely identify cartilaginous scaphoid ridge or lunate facets. Although the scaphoid ridge could be identified in the coronal plane, this could not be achieved routinely. Subsequently, MRI could not be used to determine scaphoid type. Lunate type could be routinely differentiated using coronal MRI, including lunates with small cartilaginous ulnar facets.
Morphological midcarpal variants:

1. Scaphoid type could only be accurately determined at dissection (Figure 4.1). Clinically, this finding suggests that scaphoid type can be determined only at arthroscopy with visual inspection of the distal scaphoid STT articular surface.

Figure 4.1

The dissected specimen has been opened dorsally to expose the midcarpal and radiocarpal joints. A A type 1 scaphoid in which the distal articular surface of the scaphoid surface is smooth and flat. B A type 2 scaphoid, displaying the distal articular surface of the scaphoid, which is double-faceted, with a clear ridge corresponding to the direction of trapezio-trapezoidal articulation. From – Viegas (2001).
Lunate type could only be accurately determined by combined MRI imaging and visualization at arthroscopy or at dissection. Although large lunate facets could be routinely identified by plain AP radiographs and coronal CT scans, lunates with small, cartilaginous facets were identifiable only with either coronal MRI (Figure 4.2) or at dissection. Lunate type was best described as a spectrum, with a single-faceted at one end, double-faceted at the other, and a cartilaginous-only group lying in-between.

Figure 4.2

A coronal MRI of the wrist, showing a small, cartilaginous ulnar lunate facet for articulation with the hamate. The capitate has a spherical appearance typical of the S-shaped type capitate. From – McLean et al (2009).
3. Hamate type could only be accurately determined by 3-D CT or at dissection. 3-D CT provided the best method of visualization of the hamate joint surface and the distal ridge (Figure 4.3). The surface of the hamate could be moved in 3-D and viewed in any plane, and the presence or absence of the distal ridge could be thoroughly examined.

Figure 4.3

3-D volar reconstructions of the carpus. The proximal row is represented by semitransparent osseous elements. Three-dimensional reconstruction allows 360° visualization of the osseous elements being investigated. A. The absence of a groove at the triquetro-hamate joint is characteristic of a type I hamate. B. In comparison, the spiral configuration of the hamate groove is well visualized with this modality and is typical of a type II hamate. From – McLean et al (2009).
Capitate type could not be routinely identified by plain AP radiographs. Coronal CT and MRI imaging could accurately differentiate F-type from the other types, but could not routinely differentiate S type and V-type capitates. Accurate interpretation of capitate type required extensive dissection.

**Figure 4.4**


A. A flat type (F-type) capitate, characterized by a horizontal lunate articulation and a nearly vertical scaphoid articulation.

B. A V-shaped (V-type) capitate, characterized by separate lunate and scaphoid facets that converge, separated by a visible ridge, corresponding to the direction of the scapholunate joint.

C. A spherical (S-type) capitate, characterized by a round capitate head, with an associated concave articulation formed by the scaphoid and lunate facets.
Chapter 5 – INVESTIGATION OF INCIDENCE OF STT OA IN A POPULATION GROUP

5.1 Introduction

The research performed investigates whether an association exists between lunate morphology and midcarpal osteoarthritis. The paper is discussed, with the research aims and objectives of the study being outlined. It includes the principles of study methodology and the main findings of the published research. It is not a restating of the published paper.

5.2 Paper title

An association between lunate morphology and scaphoid-trapezium-trapezoid arthritis (Appendix 3)

5.3 Research aims

The aim was to assess whether an association exists between scaphoid-trapezium-trapezoid (STT) osteoarthritis (OA) and lunate morphology.

5.4 Research objectives

To determine the lunate type, as described by Viegas et al. (1990), using plain postero-anterior radiographs.

To correlate the type of lunate with age, sex, handedness and presence/absence of STT OA.

To determine if an association exists between lunate type and STT OA.

5.5 Research performed

Plain neutral postero-anterior radiographs were evaluated for 85 patients with established STT arthritis and 140 patients from a control group, over the age of 50 years.

Lunate morphology was determined by two independent observers, using the method of Viegas et al. (1990). A Type 1 lunate was defined as a lunate with a single distal facet for the
capitate. A type 2 lunate was defined as having two distal facets; a radial facet for articulation with the capitate and an ulnar facet for articulation with the hamate.

All radiographs were reviewed by two independent observers, on two separate occasions. Intra- and inter-observer kappa statistics were performed to assess agreement.

Standard $t$ tests, Fisher’s exact tests and linear regression methods were used to analyze the data, with statistical significance being defined as p-value < 0.05.

**5.6 Main finds of the published research**

There was no statistically significant difference between the two groups when comparing age, gender or handedness. There was no significant difference between genders in the distribution of type 1 and type 2 lunates.

There was a statistically significant difference between the two groups when comparing lunate type. A higher proportion of type 2 lunate wrists were found in the STT OA group.

Intra-variability and inter-variability was rated as low.
Chapter 6 – A NEW CLASSIFICATION CONCEPT FOR COMPLEX CARPAL INJURIES

6.1 Introduction

The research performed presents a modification to Johnson’s widely-accepted perilunate injury classification system (Johnson, 1980). The paper is discussed, with the research aims and objectives of the study being outlined. It includes the principles of study methodology and the main findings of the published research. It is not a restating of the published paper.

6.2 Paper title

Trans-lunate Fracture With Associated Peri-lunate Injury: 3 Case Reports With Introduction of the Trans-lunate Arc Concept (Appendix 4)

6.3 Research aims

To present a modification to Johnson’s widely-accepted peri-lunate injury classification system.

6.4 Research objectives

1. To collect case studies of rare trans-lunate, peri-lunate fracture-dislocations and discuss their management.

2. To present the current widely-accepted classification systems used in the management of lunate fractures and peri-lunate fracture-dislocations, and to compare trans-lunate peri-lunate fracture dislocations to these current classification systems.

3. To introduce the “trans-lunate arc” concept and present a modification to Johnson’s widely-accepted peri-lunate injury classification system (Johnson, 1980).

4. To outline the management principles for the “trans-lunate arc”, including salvage options.
6.5 Research performed

Three rare trans-lunate, peri-lunate fracture-dislocation were identified in a 12 month period.

Clinical information was collected on each case, including the presenting mechanism of injury, pre-operative work-up, operation details and post-operative plan. This included collating and assessing all radiographic and magnetic resonance imaging used in the patients’ assessments.

Patients were followed up at six, 12 and 26 weeks post-operatively. Follow-up included plain radiographic x-rays and functional assessments. The functional assessments included objective clinical scores (Gartland and Werley, 1951; Knirk and Jupiter, 1986; Solgaard, 1988) and subjective Disabilities of Arm, Shoulder and Hand (DASH) scores (Hudak et al., 1996). Where plain radiographs demonstrated loss of fixation, further imaging was collected.

Where patients had an unplanned return to theatre, an intra-operative functional assessment of stability was made and recorded by fluoroscopic assessment. These patients were further followed up at six and 12 weeks post-operatively. Follow-up included plain radiographic x-rays and further subjective and objective functional assessments.

6.6 Main finds of the published research

Trans-lunate, peri-lunate fracture-dislocations are a rare presentation, which usually result from a high-energy trauma. They are often not isolated injuries, but are commonly associated with concurrent systemic injuries. There is a tendency for associated greater arc and lesser arc injuries.

In trans-lunate fractures, the degree of lunate displacement depends on the destabilizing forces acting on the lunate fracture fragments. The forces influence the fracture pattern, the associated damage to direct supporting ligaments of the lunate, and the associated damage to indirect supporting carpal structures. The long radiolunate and short radiolunate ligaments, the ulnolunate ligament, and the scapholunate and lunotriquetral ligaments may provide substantial destabilizing effects, which should be considered in any trans-lunate fracture.

With a combined trans-lunate peri-lunate fracture-dislocation, the surgeon cannot stabilise the proximal carpal row to the stable “keystone” lunate, as the lunate is unstable. These injuries
are more severe, more difficult to treat, and are more likely to have a bad prognosis. There is potential difficulty in achieving satisfactory lunate reduction and fixation in the presence of coincident lesser arc and/or greater arc perilunate injury.

If the lunate is fractured, then the treatment algorithm must be altered. The surgeon must aim to stabilise the lunate first, and then stabilise the proximal carpal row. The associated lunate fracture makes the stabilization process considerably more difficult.

The management principles of a trans-lunate arc injury should be directed toward the reduction and fixation of the lunate, with concurrent repair of any coincident lesser arc or greater arc dysfunctions.

Figure 6.1

Perilunate injury patterns showing greater arc, lesser arc, and translunate arc. Line 1 indicates greater arc injuries, which occur through osseous structures surrounding the lunate, such as the radial styloid, scaphoid, capitate, hamate, and triquetrum. Line 2 indicates lesser arc injuries, which occur through the direct ligamentous structures surrounding the lunate. Line 3 indicates translunate arc injuries, which occur through the osseous lunate. From - Bain et al. (2008).

NOTE:
This figure is included on page 57 of the print copy of the thesis held in the University of Adelaide Library.
The combined, rare condition of trans-lunate, peri-lunate fracture-dislocation, is not included in the instability pattern as described by Mayfield (1984) and Johnson (1980), nor the classification of lunate fractures as described by Teisen and Hjarbaek (1988). Consequently, a modification to Johnson’s widely accepted classification system of perilunate instabilities is proposed. The term *trans-lunate arc* is proposed to include all trans-lunate fractures, with associated peri-lunate injury (fracture, dislocation, or subluxations). The term is to be used in conjunction with the terms *greater arc* and *lesser arc* when classifying peri-lunate injuries.
Chapter 7 – CONCLUSION

7.1 Introduction

The conclusion provides an overriding discussion of the work presented in the thesis. It includes comments on the significance of the work, problems encountered and future research. It is not aimed to be a detailed reworking of the discussion of each paper published.

7.2 Linkage between publications

The work described in the thesis has made advances in a number of areas. There has been a development in the understanding of the morphology of the normal wrist joint and how the morphology interacts with pathomechanical processes.

The literature review (Chapter 2) highlighted several areas where there were deficiencies in the knowledge where further research was indicated. This formed the basis for establishing the research purpose and aims.

Chapter 3 outlined the cumulative understanding of classical anatomists, arthroscopists and various imaging modalities, with regard to the scaphoid. It presented the current understanding of the scaphoid in regard to surface anatomy, osteology, ligamentous constraints, vascularity; and its articulating joints. The known associations of different scaphoid types were presented in relation to scaphoid kinematics, scapholunate instability and scaphoid-trapezium-trapezoid arthritis. Chapter 3 identified areas of future research, especially in relation to the potential associations between different scaphoid morphologies and various carpal pathomechanical processes.

Research to date has identified and described other carpal morphological variants, specifically different types of lunate (Viegas et al., 1990), triquetrum (McLean et al., 2006), capitate (Yazaki et al., 2008) and hamate (McLean et al., 2006). The identification of these morphological variants has led to investigations that compared morphological type with differences in ligament composition and distribution, differences in carpal kinematics and pathomechanics, different techniques for imaging interpretation, and variations in surgical outcomes. This has led to a new understanding of the relationship between carpal morphology and the development of different carpal pathologies.
Viegas (1990) classified two types of lunate based on the midcarpal distal articulation of the lunate, as alluded to by previous investigators. In this description, a type 1 lunate has a single distal facet for the capitate, and it does not articulate with the hamate. In contrast, a type 2 lunate has two distal facets: the radial facet articulates with the capitate, and the ulnar facet articulates with the hamate. Differences in lunate type have been reported to be associated with variations in ligament composition and distribution, (Viegas, 2001a; Viegas et al., 1993c; Viegas et al., 1993d), carpal kinematics (Nakamura et al., 2000; Viegas, 2001b) and pathomechanics, (Galley et al., 2007) and various carpal pathologies (Haase et al., 2007; Nakamura et al., 2001; Sagerman et al., 1995a; Viegas, 1990a, 2001b; Viegas et al., 1993c). This begs the question whether similar associations exist for the other identified carpal morphological variants. Viegas et al. (1993) reported that midcarpal OA at the lunate-hamate joint was largely confined to type 2 lunate wrists, suggesting that wrist morphology was a determinant in the development of midcarpal OA. Several investigators have suggested that variations in morphology contribute to differences in carpal kinetics, joint loading and soft tissue constraints, which influence the patterns of OA seen at the wrist (Haase et al., 2007; Nakamura et al., 2001; Pfirrmann et al., 2002).

The shape of the lunate influences the movement of the scaphoid, during ulnar and radial deviation (Nakamura et al., 2000; Viegas, 2001b). Some researchers have postulated that arthritic erosion of the STT joint loosens the constraints of the STT articulation, resulting in instability at the STT joint (Ferris et al., 1994). Others have proposed loss of articular congruity (Ferris et al., 1994) or instability of the STT joint (Meier et al., 2003) as causes of STT OA. These hypotheses suggest that whether STT OA is a cause or the consequence of instability of the STT joint, alterations in the normal kinematics of the STT joint are associated with STT OA. As motion at the STT joint is closely related to scaphoid kinematics, it is possible that variations in lunate morphology may be related to the pathogenesis of STT OA. Chapter 5 investigated whether an association exists between scaphoid-trapezium-trapezoid (STT) osteoarthritis (OA) and lunate morphology, and found that type 2 lunate wrists were associated with STT OA.

Galley et al. (2007) investigated the relationship between lunate morphology and scaphoid kinematics, and demonstrated that wrists with different lunate morphology have significantly different kinematics during radial-ulnar deviation of the wrist. Specifically, wrists with a type 1 lunate show greater scaphoid translation, while wrists with a type 2 lunate show greater
scaphoid flexion (Galley et al., 2007). This supports the view that carpal mechanics are integrally related to the different morphologies of the wrist. Indeed, some researchers have suggested that the presence of distinct ridges of different morphological types are capable of restricting rotational movements at those joints, thus producing the differences in carpal kinematics observed in the literature (Moojen et al., 2003; Moritomo et al., 2004; Moritomo et al., 2000a; Pinto et al., 2003). Other researchers support the view that the ridges and grooves that define morphological variants are formed as a consequence of motion at their respective joint surfaces, and are not a factor influencing it (Galley et al., 2007). These dichotomous theories are likely to both be correct at different phases through the various carpal kinematic movements. It is most likely that there is a combination of these two theoretical mechanisms operating through different complex carpal kinematic movements, with a spectrum of variation in-between.

Fogg (2004) suggested that the ridge formed at the STT joint (type II distal scaphoid) was cartilaginous, and likely to be formed as a consequence of linear motion at the STT joint. Similarly, Galley et al. (2007) suggested that the linear ridge that defined a type 2 lunate was likely to be formed as a consequence of linear motion at the midcarpal joint. These studies would suggest that whether the linear ridges that define their respective carpal morphologies are a cause of, or the consequence of differences in carpal kinematic patterns, morphology could be used as an indicator of motion pattern at that particular joint. Specifically, the presence of a ridge may be an “indicator” of a single plane linear motion pattern at that joint, while a smooth articular surface would represent a combination of linear and rotational motions.

By far the greatest volume of research comparing morphological type with carpal kinematics, has been with regard to the lunate (Fogg, 2004; Nakamura et al., 2000). This is likely because lunate type can be easily identified using non-invasive techniques that preserve the extrinsic ligaments and tendons being investigated (Galley et al., 2007). However, most current research on carpal kinematics has been completed without regard to morphological types (Feipel and Rooze, 1999b; Gardner et al., 2006; Kaufmann et al., 2006; Leonard et al., 2005; Moojen et al., 2002a; Moritomo et al., 2000a; Moritomo et al., 2000b; Patterson et al., 1998; Sun et al., 2000; Viegas et al., 1990; Wolfe et al., 2006). This has limited the advancement in our understanding of carpal kinematics and pathomechanics, and any differences that might be related to variations in morphologic features. Although several studies have used the
presence or absence of linear ridges to define various carpal morphological types, the exact relationship between carpal morphology and carpal mechanics has not been investigated for several reasons.

Firstly, in order to perform a comprehensive examination of the relationship between carpal morphology and carpal mechanics, a method of identifying the various carpal morphologies using a non-invasive technique is required. This would allow preservation of the ligamentous and osseous features under investigation, thus enabling an accurate way of comparing the anatomic and mechanical properties of each carpal morphology. However, many of the descriptions of carpal morphologies in the literature have relied on direct visualisation of the articular surfaces to establish a typing. As many of the carpal ligaments and osseous features that categorize these morphologies cannot be visualised without the extrinsic ligaments and tendons being incised and removed, a clear standard for identification of these morphological variants using non-invasive techniques must be established. Chapter 4 addressed this deficiency in the literature and established a standard for non-invasive identification of the midcarpal anatomical variants by different imaging techniques. This chapter identified that scaphoid type could only be accurately determined at dissection, suggesting that scaphoid type can only be determined at arthroscopy with visual inspection of the distal scaphoid STT articular surface. In contrast, lunate, capitate and hamate types could be determined with varying accuracies using each imaging technique. This chapter established that the best technique for identifying lunate type was MRI, and for hamate type was 3-D CT reconstruction. Capitate type could be differentiated into F-type and other types, but could not routinely differentiate S type and V-type capitates, suggesting that accurate interpretation of the capitate type required extensive dissection. This knowledge will improve the understanding of carpal kinematics and pathomechanics and any differences that might be related to these variations in morphologic features.

Secondly, the associations between various individual carpal morphologies has not been investigated. Specifically, the incidence of scaphoid, triquetral, hamate and capitate types has not been established. A simple correlation analysis of carpal morphologies using a large sample size would assist in answering this question. However, such a correlation analysis would be most useful if the parameters that defined each morphological variant using non-invasive imaging techniques were investigated concurrently. Since Chapter 4 has determined the best method for identification of the various carpal morphological variants, a correlation
analysis of the various carpal morphologies can now be undertaken. If a clear pattern of wrist morphology does exist, the differences in carpal kinematics and pathomechanics related to wrist morphology can be more easily investigated. Further research is needed to address these questions.

Chapter 5 hypothesized that a correlation analysis of carpal morphologies would establish that there are two (possibly three) distinct wrist morphological types, with a spectrum of variation in-between. Furthermore, Chapter 5 hypothesized that these wrist types have different ligament composition and distribution, different carpal kinematics and pathomechanics, and different incidences and predispositions to various carpal pathologies. However, further research is needed to test this hypothesis.

Thirdly, before the relationship between carpal morphology and carpal mechanics can be fully investigated, a clear standard for identification of these morphological variants must be established. Chapter 4 addressed this third point. Specifically, the aim was to establish a clear standard for accurate recognition of these variants using different imaging techniques. Chapter 4 presented the findings of this study, which demonstrated that lunates with a small, cartilaginous ulnar facet (intermediate type) could be differentiated only by coronal MRI and by dissection. Scaphoid type could not be determined accurately using any of the imaging modalities described, and clinically this finding would suggest that scaphoid type could only be determined at arthroscopy with visual inspection of the distal scaphoid STT articular surface. Capitate type was most accurately determined from coronal MRI, but flat and spherical-type capitates could not be routinely differentiated from V-shaped capitates. Hamate type was most accurately determined from 3-dimensional CT reconstruction.

While investigating the differences in ligament composition and distribution attributable to carpal morphologies, we reviewed the pathomechanics of various common carpal conditions. One of these was scapho-lunate instability. Haase et al. (2007) reported that type II lunate morphology was associated with a decreased incidence of dorsal intercalated segment instability (DISI) deformity in cases of established scaphoid non-union (Moore et al., 2007). Scaphoid non-union is a condition well known to predispose to carpal instability, specifically DISI deformity. Haase et al. (2007) theorized that a type II lunate’s articulation with the hamate lends some additional stability that resists abnormal extension. They suggested that the triquetrum’s usual “extension moment,” caused by force transmitted through its screw-like
articulation with the hamate, was halted by the lunatohamate articulation present in type II midcarpal joints.

As a consequence of this finding, the available literature on lunate fractures was reviewed, in an attempt to determine whether the same principle applied to trans-lunate fractures. However, no literature that addressed the potential association(s) between carpal morphology and trans-lunate fractures was found. What was identified was that isolated fractures of the lunate were rare (Haase et al., 2007; Kuderna, 1986; Razemon, 1988) and that these trans-lunate fractures were commonly associated with a combination of co-incident ligament ruptures and other carpal fractures. In addition, the combined, rare condition of trans-lunate, peri-lunate fracture-dislocation was not included in the instability patterns described by Johnson (1980) or Mayfield (1984), or in the classification of lunate fractures described by Teisen and Hjarbaek (1988). A trans-lunate fracture, combined with rupture of the scapholunate or lunotriquetral ligaments produces a supplementary destabilizing force, distinct from the translation force exerted by the capitate, typical of a stage IV peri-lunate dislocation described by Mayfield (1984). The destabilizing effect secondary to a lunate fracture was not investigated by Mayfield (1984). Indeed, a lunate fracture should be considered as an independent, supplementary destabilizing force to be considered when attempting to classify peri-lunate instabilities.

In trans-lunate fractures, the degree of lunate displacement depends on the destabilizing forces acting on the lunate fracture fragments. The forces influence the fracture pattern, the associated damage to direct supporting ligaments of the lunate, and the associated damage to indirect supporting carpal structures. The long radiolunate and short radiolunate ligaments, the ulnolunate ligament, and the scapholunate and lunotriquetral ligaments may provide substantial destabilizing effects, which should be considered in any trans-lunate fracture. The combined destabilizing properties of these ligaments have not yet been investigated by any laboratory analysis.

With a peri-lunate dislocation, the volar radiolunate ligaments remain intact, stabilizing the lunate to the radius. When performing a surgical stabilization of a peri-lunate fracture-dislocation, the surgeon will often stabilize the proximal carpal row to the stable “keystone” lunate. If the lunate is also fractured, then the treatment algorithm must change—-with the surgeon aiming to stabilize the lunate first, and then stabilize the proximal carpal row. The associated lunate fracture makes the stabilization process considerably more difficult.
Identifying this gap in the literature, we proposed a modification to Johnson’s widely accepted classification system of peri-lunate instabilities (Johnson, 1980); specifically, the addition of a third category of peri-lunate instability that recognizes the destabilizing forces resulting from, and consequent to, a concurrent lunate fracture. Chapter 6 described a series of rare trans-lunate, peri-lunate fracture-dislocations. In this chapter, the term “trans-lunate arc” was proposed to include all trans-lunate fractures, with associated peri-lunate injury (fracture, dislocation, or subluxations). This term was proposed to be used in conjunction with the widely-accepted terms greater arc and lesser arc when classifying peri-lunate injuries. Chapter 6 also outlined the management principles and prognosis for the trans-lunate arc injuries, compared to greater arc and lesser arc injuries.

7.3 Future research

If non-invasive techniques of investigation are utilised, then a simple means of determining morphological type can be employed. This would preserve the extrinsic ligaments and tendons under investigated and enable future research to concentrate on comparing the anatomic and mechanical properties of each carpal morphology under investigation. This would advance our understanding of carpal kinematics and pathomechanics, and any differences that might be attributed to variations in morphologic features.

As is the case with most theses, more questions are raised than can be addressed in a candidature. Hopefully, by identifying areas of question within the literature and offering a potential method for addressing these questions, future researchers may have a framework on which to build on their aims and contribute to the accumulative knowledge.

7.3.1 Carpal morphology

This Thesis identified other deficiencies in the knowledge of wrist anatomy, imaging and surgical management that require further research:

Question identified: What are the quantitative parameters that define a:

1. ridge (scaphoid, hamate, capitate or lunate)
2. groove (scaphoid, hamate, triquetral)
3. fossa (scaphoid, hamate, capitate, triquetral or lunate)

*Aim:* To establish the quantitative parameters that define a ridge, groove and fossa.

*Significance of the aim:* The nomenclature and definitions of the various carpal ridges, grooves and fossae have not been established. A clear standard for accurate recognition and interpretation of these morphological variations would improve the understanding of carpal kinematics and pathomechanics and any differences that might be related to these variations.

*Clinical relevance:* Non-invasive surface- and volume-rendered images can be produced using CT and MRI computer software. These virtual images can be used to investigate carpal kinematics in the normal and abnormal wrist to improve the understanding of instability of the wrist.

*Potential method of addressing question:* A quantitative analysis of the angles and measurements of the ridges, grooves and fossae that define each morphological variant. Investigation currently in progress.

### 7.3.2 Scaphoid

*Question identified:* What is the incidence of different ligament composition and distribution between different scaphoid types?

*Aim:* To determine whether ligament restraints differ between scaphoid types.

*Significance of the aim:* Establishing whether a difference in ligament composition exists between different scaphoid types would improve the understanding of the normal and abnormal wrist. An improved understanding of the differences in ligament composition and orientation would aid in the planning of operations on the wrist.

*Clinical relevance:* Differences in carpal ligament anatomy would necessitate different considerations when planning surgery to the wrist.

*Potential method of addressing question:* A combined MRI, dissection, and histological study of scaphoid anatomy.
7.3.3 Capitate

*Question identified:* Is capitate morphology related to the incidence of midcarpal OA?

*Aim:* To determine whether capitate morphology is related to the incidence of midcarpal OA.

*Significance of the aim:* Establishing whether capitate type is associated with OA would improve the understanding of the pathomechanics of midcarpal OA. An improved understanding of midcarpal OA would aid in the planning and management of wrist OA.

*Clinical relevance:* Advanced midcarpal OA is an indication for fusion in symptomatic patients. Capitate type could be used as a predictor for the development of OA in patients suffering traumatic carpal instability.

*Potential method of addressing question:*

1. A clinical correlation of capitate type comparing a control group with a midcarpal OA group.

2. A cadaveric study reporting the incidence of capitate type and the incidence of midcarpal OA.

7.3.4 Lunate

*Question identified:* Is lunate morphology related to the incidence of trans-lunate fracture?

*Aim:* To determine whether lunate morphology is related to the incidence of trans-lunate fracture.

*Significance of the aim:* Establishing whether lunate type is associated with the incidence of trans-lunate fracture would improve the understanding of the pathomechanics of carpal instability. An improved understanding of trans-lunate fractures would aid in the planning and management of traumatic injuries to the wrist.

*Clinical relevance:* Trans-lunate fractures are often managed non-operatively with varying results. Establishing whether lunate morphology is related to the incidence of trans-lunate
fracture may help the clinician in predicting the likelihood of refracture or non-union, and aid in the decision to treat operatively or non-operatively.

*Potential method of addressing question:* A clinical correlation of lunate type, comparing a control group with a trans-lunate fracture group with follow-up to determine the rates of union and non-union.

### 7.3.5 Hamate

*Question identified:* Is hamate morphology related to outcomes in the treatment of trans-hamate fracture treated by non-operative/operative, closed reduction/open reduction internal fixation?

*Aim:* To determine whether hamate morphology is related to outcomes in trans-hamate fracture management.

*Significance of the aim:* Establishing whether hamate type is associated with different outcomes in the management of trans-hamate fractures would improve the understanding of the pathomechanics of wrist trauma. An improved understanding of trans-hamate fractures would aid in the planning and management of traumatic injuries to the wrist.

*Clinical relevance:* Trans-hamate fractures are often managed non-operatively with varying results. Establishing whether hamate morphology is related to the incidence of trans-hamate fracture may help the clinician in predicting the likelihood of non-union, and aid in the decision to treat operatively or non-operatively.

*Potential method of addressing question:* A randomised controlled trial comparing the outcomes of two surgical techniques between morphological distinct groups.

### 7.3.6 Triquetrum

*Question identified:* Is triquetral morphology related to surgical outcomes in the treatment of lunotriquetral instability?

*Aim:* To determine whether triquetral morphology is related to outcomes in the management of lunotriquetral instability.
Significance of the aim: Establishing whether triquetral type is associated with different outcomes in the management of lunotriquetral instability would improve the understanding of the pathomechanics of carpal instability. An improved understanding of lunotriquetral instability would aid in the planning and management of injuries to the wrist.

Clinical relevance: Lunotriquetral ligament ruptures are typically associated with a change in carpal kinematics. Left untreated, these injuries can progress to peri-lunate subluxations or degenerative arthritis. Establishing which triquetral types are associated with poor outcomes would aid in the choice of operative procedure.

Potential method of addressing question: A randomised controlled trial comparing the outcomes of two surgical techniques between morphological distinct groups.

7.4 Summary

The work described in this thesis has addressed the perceived deficiencies in the knowledge of wrist anatomy and imaging that has limited the surgical treatment of wrist disorders. The thesis encompasses studies of the normal wrist morphology, imaging of the wrist, and the development of a classification system to address the management of complex carpal injuries.

The problem areas identified which were addressed included (i) the morphology of the normal wrist, (ii) imaging techniques of morphological variants, (iii) morphological association with midcarpal osteoarthritis, and (iv) the clinical application of classification systems for the management of complex carpal injuries.

To address these deficiencies, a combined radiographic and MRI study was undertaken to determine the best method for identification of the various morphological variations of the articular surfaces at the midcarpal joint, using non-invasive imaging techniques. Of significance, a clear standard for accurate recognition of these variants using different imaging techniques was established. An inter-observer reliability study was undertaken to establish the reproducibility of the techniques, and to compare the results with previously reported data. A correlation analysis of the various carpal morphologies can now be undertaken.
A radiographic investigation established that lunate morphology was related to the incidence of midcarpal OA. This supports the notion that carpal morphology is related to the pathomechanics of various carpal conditions.

A clinical review established an inclusive classification system for the management of complex carpal injuries. The term *trans-lunate arc* was introduced to include all trans-lunate fractures, with associated peri-lunate injury (fracture, dislocation, or subluxations).

The work described in this thesis increases the knowledge of the normal wrist morphology and imaging. It further advances the knowledge of pathomechanics related to wrist morphology and presents a new understanding in regard to the principles in the management of complex carpal injuries.
LIST OF TABLES

Table 2.1

Distinguishing features between type I and type II hamates (McLean et al., 2006)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Type I hamate</th>
<th>Type II hamate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal articulating surface</td>
<td>volar ellipsoid convexity</td>
<td>central ellipsoid convexity</td>
</tr>
<tr>
<td>Distal volar concavity</td>
<td>Prominent</td>
<td>Slight</td>
</tr>
<tr>
<td>Hamate groove</td>
<td>Present</td>
<td>Absent</td>
</tr>
<tr>
<td>Hamate ridge</td>
<td>Present</td>
<td>Absent</td>
</tr>
</tbody>
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LIST OF FIGURES

Figure 1.1

The Ebers Papyrus was an important medical papyri of ancient Egypt produced about 1550 BC. It is one of the two oldest preserved medical documents known, the other being the Edwin Smith papyrus (around 1600 BC). The Ebers Papyrus was written in hieratic Egyptian and contains some 700 magical formulas and remedies. It contains many incantations meant to turn away disease-causing demons, in addition to providing evidence of a long tradition of empirical practice and observation. The papyrus itself is a 110-page scroll, which is about 20 meters long.

Figure 1.2

A late thirteenth-century illustration of the venous system within the body. The majority of the anatomical texts of this time were based on the work of Galen. According to Galen, the venous system was distinct from the arterial, and the blood ebbed and flowed through the body.

Figure 1.3

An anatomical drawing from De Humani Corpis Fabrica (On the Fabric of the Human Body), written in 1543 by Andreas Vesalius (1514-1564). Vesalius discovered that a number of Galen's teachings were based on the incorrect assumption that dog anatomy was similar to human anatomy. By delving into the workings of the human body, Vesalius was able to correct 200 previously unquestioned theories on human anatomy. His work brought a number of important changes to the study of anatomy. Most importantly, Vesalius repeatedly stressed the idea that students must not depend upon the teachings of their elders, but must explore the inner workings of the human body for themselves.

Figure 1.4

Rembrandt van Rijn’s The Anatomy Lesson of Dr. Nicolaas Tulp (1632). In this painting the eminent surgeon stands surrounded by students as he demonstrates the workings of the forearm muscles and tendons. Despite debate over the origin of the forearm flexor muscle
mass as depicted in this painting dissection of the upper extremity clearly was important to anatomists. (From - Mauritshuis, the Hague).

**Figure 1.5**

A photograph of Henry Gray, the original author of *Gray's Anatomy of the Human Body*, an English-language human anatomy textbook widely regarded as a classic work on the subject. The book was first published under the title *Gray's Anatomy: Descriptive and Surgical* in the United Kingdom in 1858, and the following year in the United States. While studying the anatomical effects of infectious diseases, Gray contracted smallpox from his dying nephew and died shortly after the publication of the 1860 second edition, at the age of 34. The text has been revised many times and is now in its 39th British edition.

**Figure 1.6**

Wood block illustration from Vesalius showing the numbering scheme applied to the carpus. From – Dobyns (1997)

**Figure 1.7**

In 1895, the German physicist Wilhelm C. Röntgen (1845-1923) discovered electromagnetic radiation in a wavelength range today known as x-rays. This achievement earned him the first Nobel Prize in Physics in 1901. **Insert**: Wilhelm Röntgen's first "medical" x-ray, of his wife's hand, taken on 22 December 1895.

**Figure 1.8**

An X-ray picture (radiograph) taken by Röntgen of Albert von Kölliker's hand on 23 January 1896, one month after the first "medical" x-ray, of his wife's hand. The improvement in technique is evident by the improved resolution of the metacarpals and phalanges.

**Figure 1.9**

A picture of Sir Godfrey Hounsfield (28 Aug 1919 – 12 Aug, 2004) standing next to the computed tomography scanner he developed. He shared the 1979 Nobel Prize for Physiology or Medicine with Allan McLeod Cormack for his part in developing the diagnostic technique of X-ray computed tomography.
Figure 1.10

A photograph of Nikola Tesla (1856-1943) was an inventor and a mechanical and electrical engineer. He was credited with many revolutionary contributions to the field of electricity and magnetism in the late 19th and early 20th centuries. Tesla's patents and theoretical work formed the basis of electromagnetism, modern alternating current electricity (AC) systems, including the polyphase power distribution systems and the AC motor, with which he helped usher in the Second Industrial Revolution.

Figure 1.11

Radiocarpal-joint injection. First described by Kessler and Silberman (1961), radiocarpal-joint injections can evaluate both the TFCC and the scapholunate and lunotriquetral ligaments. In this case, all are intact, with contrast medium maintained within the radiocarpal articulation and no abnormal communication with the adjacent joint compartments.

Figure 1.12


Figure 2.1

Dissected specimens of the midcarpal joint opened dorsally. C: capitate; H: hamate; L: lunate; S: scaphoid; T: triquetrum. From - Yazaki et al. (2009). A. A flat type (F-type) capitate, characterized by a horizontal lunate articulation and a nearly vertical scaphoid articulation. B. A V-shaped (V-type) capitate, characterized by separate lunate and scaphoid facets that converge, separated by a visible ridge, corresponding to the direction of the scapholunate joint. C. A spherical (S-type) capitate, characterized by a round capitate head, with an associated concave articulation formed by the scaphoid and lunate facets.
Figure 2.2


Figure 2.3

A proximal view of the hamate (looking from the ulnar side of the right hand toward the digits). A. A spiral-type hamate showing the hamate groove (HG) and distal ridge (DR). B. A flat-type hamate with no distal ridge or hamate groove. HH: hook of hamate; PAS: proximal articulating surface. From – McLean et al. (2006).

Figure 2.4

The proximal aspect of the capitate (C) and the hamate (H) showing the ridge (double arrow) on the hamate that corresponded to the recess of the lunotriquetral joint and a ridge (one arrow) on the capitate that corresponded to the recess of the scapholunate joint. From - Viegas et al. (1990a).

Figure 2.5

The dorsoulnar aspect of the hamate (looking toward the center of the palm from the lateral side of where the extensor carpi ulnaris traverses over the carpal bones). A. A type I hamate showing the hamate groove (HG) and distal ridge (DR). B. A type II hamate with no distal ridge. There is a hamate ridge (HR) on the proximal articulating surface, which signifies that this hamate articulates with a type 2 lunate. From – McLean et al. (2006).

Figure 2.6

A dorsal view of A. a spiral-type hamate and B. a flat-type hamate (looking from the dorsum of the wrist to the hypothenar eminence). DR: distal ridge; HG: hamate groove; PAS: proximal articulating surface. Compared with the spiral-type hamate (A), there is no distal ridge or hamate groove, in a flat-type hamate, as shown in B. From – McLean et al. (2006).

Figure 2.8
The ulnar aspect of the midcarpal joint showing a Type I lunate that does not have a medial hamate facet. (S: scaphoid; L: lunate; T: triquetrum).

**Figure 2.9**

Type 1 lunate. A wrist radiograph of a type 1 lunate, with a single distal facet for the capitate; it does not articulate with the hamate. From – Galley et al (2007).

**Figure 2.10**

Type 2 lunate. A wrist radiograph of a type 2 lunate, with two distal facets; the radial facet articulates with the capitate, and the ulnar facet articulates with the hamate. From – Galley et al (2007).

**Figure 2.11**

The triquetro-hamate articulating surface of a helicoidal (A) and a flat triquetrum (B). A. A helicoidal triquetrum has a broad proximal joint surface and narrow distal joint surface. This forms a helicoidal joint configuration with the hamate, with double-faceted, complementary concave and convex parts. B. In contrast, in a flat triquetrum, the joint surface remains broad distally and is almost flat. This forms a predominantly oval convex joint configuration with the hamate, where the primarily concave triquetrum is described as a “dish” for the flatter hamate

**Figure 2.12**

The proximal aspect of the capitate (C) and the hamate (H) showing the cartilage erosion with exposed subchondral bone that often was seen associated with the type 2 lunate. From – Viegas et al. (1990).

**Figure 2.13**

Johnson’s classification of peri-lunate instabilities. Greater arc GA injuries occur through osseous structures surrounding the lunate, such as the radial styloid, scaphoid, capitate, hamate, and triquetrum. Lesser arc (LA) injuries occur through the direct ligamentous structures surrounding the lunate, including the lunotriquetral and scapholunate ligaments.
Figure 2.14

Mayfield’s 4 stages of peri-lunate instability. Stage I is disruption of the scapho-lunate ligament. Stage II is dislocation (usually dorsal) of the capito-lunate articulation. Stage III is disruption of the luno-triquetral ligament. Stage IV involves tearing of the dorsal radio-carpal ligaments. From - Mayfield (1984).

Figure 4.1

The dissected specimen has been opened dorsally to expose the midcarpal and radiocarpal joints. A A type 1 scaphoid in which the distal articular surface of the scaphoid surface is smooth and flat. B A type 2 scaphoid, displaying the distal articular surface of the scaphoid, which is double-faceted, with a clear ridge corresponding to the direction of trapezio-trapezoidal articulation. From – Viegas (2001).

Figure 4.2

A coronal MRI of the wrist, showing a small, cartilaginous ulnar lunate facet for articulation with the hamate. The capitate has a spherical appearance typical of the S-shaped type capitate. From – McLean et al (2009).

Figure 4.3

3-D volar reconstructions of the carpus. The proximal row is represented by semitransparent osseous elements. Three-dimensional reconstruction allows 360° visualization of the osseous elements being investigated. A. The absence of a groove at the triquetro-hamate joint is characteristic of a type I hamate. B. In comparison, the spiral configuration of the hamate groove is well visualized with this modality and is typical of a type II hamate. From – McLean et al (2009).

Figure 4.4

Dissected specimens of the midcarpal joint opened dorsally. C: capitate; H: hamate; L: lunate; S: scaphoid; T: triquetrum. From - Yazaki et al. (2009). A. A flat type (F-type) capitate, characterized by a horizontal lunate articulation and a nearly vertical scaphoid articulation. B. A V-shaped (V-type) capitate, characterized by separate lunate and scaphoid facets that converge, separated by a visible ridge, corresponding to the direction of the scapholunate joint. C. A spherical (S-type) capitate, characterized by a round capitate head, with an associated concave articulation formed by the scaphoid and lunate facets.
Figure 6.1

Perilunate injury patterns showing greater arc, lesser arc, and translunate arc. Line 1 indicates greater arc injuries, which occur through osseous structures surrounding the lunate, such as the radial styloid, scaphoid, capitate, hamate, and triquetrum. Line 2 indicates lesser arc injuries, which occur through the direct ligamentous structures surrounding the lunate. Line 3 indicates translunate arc injuries, which occur through the osseous lunate. From - Bain et al. (2008).
ATTACHMENTS - PUBLICATIONS

Introduction

The following page lists the peer review publications presented in the thesis. The number provided before the title corresponds to the research undertaken section. The full peer-reviewed publication is then provided.

Publications

3.2 Scaphoid anatomy

Watts AC, McLean JM, Fogg Q, Bain GI.


4.2 Imaging Recognition of Morphological Variants at the Midcarpal Joint

McLean JM, Bain GI, Watts AC, Mooney LT, Turner PC, Moss M

5.2 An association between lunate morphology and scaphoid-trapezium-trapezoid arthritis

McLean JM, Turner PC, Bain GI, Rezaian N, Field J, Fogg Q
Journal of Hand Surgery (European Volume). 2009; accepted for publication 26 Jun.

6.2 Translunate fracture with associated perilunate injury: 3 case reports with introduction of the translunate arc concept

Bain GI, McLean JM, Turner PC, Sood A, Pourgiezis N
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Navarro A. 1921a. Luxaciones del carpo Anales de la Facultad de Medicina 6:113-141.


