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Methods of Estimating Bone Mineral Density in Digital Radiography

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Masters of Science

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June 2015
Declaration

I, Gregory Aidan James Robertson, hereby declare that this thesis has been composed by myself, that the work in the thesis is my own original work (except where acknowledgements indicate otherwise) and that neither the whole, nor any part of it, has been, is being or is to be submitted for any other degree in this or any other University.

G. A. J. Robertson

12th June 2015
Abstract

Assessment of bone mineral density (BMD) through Dual X-ray Absorptiometry (DXA) is a well established clinical technique. However, use of DXA is limited to the elective outpatient setting as a modality for detection of osteoporosis, and not available in the acute trauma setting prior to fracture fixation. This limits its use as a modality for estimating BMD prior to fracture fixation, and so limits its ability to influence choice of fixation materials. Given the limited resources of the current health system, such a technique of pre-operative BMD estimation would have to be performed from pre-operative plain radiographs or, more recently, pre-operative digital radiographs. Various measures have been suggested as indicators of BMD in plain radiographs, including: use of cortical measures, cortical ratios and summation of cortical measures; use of textural measures; and use of aluminium grading systems. Promising results have been reported with these measures in plain radiographs, however significant limitations exist with these techniques including variations in film quality and magnification, failure to account for the effects of soft tissue attenuation and scatter phenomenon, and inconsistent film processing techniques. With the introduction of digital imaging to clinical practice, it has been suggested that many of these limitations can be corrected for by the digital processing technique. As such, digital radiography provides clinicians with a potential tool to provide pre-operative BMD measures, allowing the potential to modify choice of fracture fixation materials accordingly. However limited research has been performed in this field to validate this technique.

In this thesis the possibility of estimating BMD from digital radiographs by comparing various methods against results obtained from DXA scanning was investigated. When considering radiographs of the hip, cortical measures and cortical indices showed good correlations with hip DXA results, with the correlation being strengthened by summations of cortical measures. Textural measure analysis showed poor correlation with hip DXA results. Use of aluminium equivalent grading showed
poor correlation with hip DXA results. When considering radiographs of the wrist, cortical measures and cortical ratios showed varying correlations with forearm and hip DXA results, ranging from poor to good. Summation of cortical measures failed to provide improved correlation values. Use of aluminium equivalent grading showed good correlation with forearm and hip DXA results.

In conclusion, this thesis shows the potential for estimation of BMD from digital radiographs in the pre-operative setting. For the proximal femur, the summation of cortical measures provided the best estimation of bone density, whereas for the distal radius aluminium equivalent grading provided the best estimate. Further analysis is however required to establish if these techniques provide an adequate indicator of fixation strength in bone and so effectively guide pre-operative selection of fracture fixations materials.
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<td>BMD</td>
<td>Bone Mineral Density</td>
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<tr>
<td>DXA</td>
<td>Dual X-ray Absorptiometry</td>
</tr>
<tr>
<td>CT</td>
<td>Computed Tomography</td>
</tr>
<tr>
<td>QCT</td>
<td>Quantitative Computed Tomography</td>
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<td>Standard Deviation</td>
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<td>World Health Organisation</td>
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<td>SIGN</td>
<td>Scottish Intercollegiate Guideline Network</td>
</tr>
<tr>
<td>NICE</td>
<td>National Institute of Health and Care Excellence</td>
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Part I

Introduction
Introduction

1.1 Subject

This study has investigated the use of digital X-ray images to facilitate pre-operative estimation of bone mineral density (BMD) and quality. Three methods were assessed: use of simple cortical measures from digital radiographs; use of simple trabecular patterns from digital radiographs and use of an Aluminium-equivalent thickness grading achieved by inclusion of an aluminium step wedge in the digital radiographs. Two sites were evaluated throughout the study: the proximal femur (hip) and the distal radius (wrist).

1.2 Background

A well-defined and consistently quantifiable method to assess BMD and bone quality pre-operatively from digital radiographs is not presently available in the standard clinical setting. Evaluation of the BMD and bone quality pre-operatively is important to allow appropriate choice of fracture fixation materials. Techniques currently used clinically, largely centre on subjective, qualitative assessment of the plain radiograph by the surgeon as well as the patient characteristics (Huber et al., 2009). Such subjective assessment, even when supplemented by quasi-quantitative measures, is variable, unreliable and strongly influenced by user-experience and interpretation (Wagner et al., 2005, Garton et al., 1994, Koot et al., 1996). Such measures are also complicated by variations in the penetration strength of the X-rays used (Chappard et al., 2010). Given the importance of the bone quality to the success of anchorage of surgical fixation materials (Court-Brown et al., 2006, Huber et al., 2009, Tingart et al., 2006, Krappinger et al., 2011, Barrios et al., 1993), more objective pre-operative techniques to allow reliable quantitative assessment of such measures would be of great clinical value.
Digital radiograph systems are relatively new to the clinical radiography environment. They offer potential in enhancing existing X-ray techniques due to their high quality digital output in which post-processing can be controlled (Nomoto et al., 2008). This allows for more accurate measurements of bone geometry and trabecular patterns as potential methods for estimating BMD (Chappard et al., 2010). They also allow digital assessment of gray penetrance, another method for assessing BMD (Nomoto et al., 2008). If digital X-ray can be used to provide quantitative measurements of BMD, it could offer benefits in the clinical setting, allowing selection of custom made orthopaedic fixations devices, based on pre-operative bone quality (Huber et al., 2009).

1.3 Context
The problems encountered in using digital radiographs to monitor BMD fall into three categories.
The first concerns the accurate translation of radiographic measures into consistent, clinically replicable measures that can be used reliably between different images and different patients.
The second involves development of a technique that can accurately assess radiation penetrance on digital radiographs.
The third involves accurate validation of such measures with measures that can be justified as the ‘gold standard’ use.

For the first concern, consideration was paid to both linear measures and textural measures. Linear measures required calibration with objects of known measure that were incorporated into the digital radiographs. Textural measures required creation of a reliable replicable technique using the contrast enhancing tools available on the digital systems.
The second problem has been dealt with in a previous PhD at our institution and reference will be made to this throughout the thesis.
The third relates to justification of use of DXA results to compare the results against and this is performed by reference to the literature.
1.4 Research Objectives

1.41 Hypothesis

Three methods of assessment of BMD from digital radiographs have been proposed:
1. Use of Cortical Measures;
2. Use of Trabecular Patterns;
3. Use of Calibration with an Aluminium Density Scale.

Based on this, the hypothesis that this thesis set out to examine was that the use of cortical measures, trabecular patterns and Aluminium calibration techniques in digital radiographs can provide pre-operative assessment of BMD at the hip (proximal femur) and wrist (distal radius), as compared to DXA results.

If such measures provide an accurate indication of BMD, then future use of such techniques in preoperative radiographs would allow surgeons to estimate the quality of bone on which they were to operate and so can direct appropriate selection of the optimal fixation materials.

1.42 Research Questions

Investigation into these three areas of pre-operative assessment of BMD from digital radiographs form the basis for the three major research questions to be answered by this thesis:
1. Can BMD be measured pre-operatively using cortical measures and ratios from digital radiographs of hip and wrist fractures?
2. Can BMD be measured pre-operatively using trabecular patterns from digital radiographs of hip fractures?
3. Can BMD be measured pre-operatively using an Aluminium Equivalent Grading in digital radiographs of hip and wrist fractures?

In answering these questions, several secondary questions will be addressed:
1. Concerned with cortical measures:
(a) Can these be measured accurately and reproducibly to represent ‘real term’ measures between different patients, equalising for the effects of image magnification?

(b) Which measures are the best indicator of BMD?

(c) Are cortical index values (cortical width : diaphyseal width ratio) more effective than simple cortical measures at estimating BMD?

(d) Are summations of cortical measures more effective than simple cortical measures at estimating BMD?

(e) Which region of DXA scanning in the hip correlates most strongly with cortical measure results around the hip?

(f) Which region of DXA scanning in the forearm correlates most strongly with cortical measure results around the wrist?

(g) Is there correlation between cortical measures around the wrist and DXA scanning results of the hip?

(h) Does rotation of the proximal femur influence cortical measure results?

2. Concerned with trabecular patterns:
(a) Can digital radiography improve accuracy in recording these measures?

(b) Do more simple groupings of trabecular patterns provide more accurate results?

(c) Which region of DXA scanning in the hip correlates most strongly with trabecular pattern measure results of the hip?

3. Concerned with aluminium step wedge assessment:
(a) Is it possible to calculate soft tissue dimensions accurately from orthogonal digital radiographs?

(b) Does correction for the Perspex Jig in the hip radiographs provide more accurate measures?

(c) Which region of DXA scanning in the hip correlates most strongly with aluminium equivalent measure results of the hip?

(g) Which region of DXA scanning in the forearm correlates most strongly with aluminium equivalent measure results of the wrist?
(h) Is there correlation between aluminium equivalent measures of the wrist and DXA scanning results of the hip?

1.5 Scope
This project aimed to evaluate the potential of digital radiographs to aid the assessment of BMD, and to identify problems associated with this. As such it involved the testing and development of methods, which aimed to assess BMD from digital radiographs. The scope of the project involved the evaluation of such techniques in clinical situations.

1.6 Investigative Process
This study consisted of three main areas: use of cortical measures, use of trabecular patterns and use of aluminium equivalent measures to assess BMD in digital radiographs, both at the hip and the wrist. To clarify the development of these ideas, the thesis is arranged in several parts.

The thesis begins with a review of the literature in Part II. This covers the conventions and problems in measuring BMD from digital radiographs and previous results of the proposed methods to be investigated.

Part III describes the methods and clinical recruitment of the study.

Part IV describes the methods used for analysis of digital radiographs in the study, including the use of the Image J programme and the use of the MatLab Programme. It provides a description and validation of methods to reliably record and compare cortical measures and trabecular patterns from digital radiographs of different patients. It also describes the method validated in a previous PhD to allow for assessment of BMD from digital radiographs using an aluminium equivalent grading, followed by a description of the modifications required to implement this into clinical practice.

Part V deals with the choice and use of DXA as the clinical gold standard measure of BMD in the study.
Part VI presents the results of using cortical measures from digital radiographs to assess BMD. It presents the results from simple cortical measures, cortical ratios and combined scores, providing data from both the hip radiographs and the wrist radiographs.

Part VII presents the results of using trabecular measures from digital radiographs of the hip to assess BMD. It presents results first from the traditional categories of trabecular patterns followed by results from the modified categories of trabecular patterns with comparisons performed between both.

Part VIII presents the results of using an aluminium equivalent grading from digital radiographs to assess BMD. The section assesses both radiographs of the hip and the wrist.

In Part IX, conclusions from the results and discussions in the previous sections are drawn.

In Part X, recommendations for extension of the work and future developments are made.
Part II
Literature Review
Literature Review

2.1 Introduction

The human skeleton has evolved to provide skeletal bone that is light enough to enable rapid mobility and strong enough to avoid disabling fractures during active adult life(Cummings and Melton, 2002). However with advancing age, skeletal bone is universally affected by decreasing bone mineral density and deterioration of bone structure, which when severe enough, results in the condition termed osteoporosis(Cummings and Melton, 2002, Johnell and Kanis, 2005, Stromsoe, 2004). This condition in itself is not a major health problem, however, the decreased biomechanical strength it imposes on the skeleton, significantly increases the probability of low impact bone fractures, and this forms a major clinical and public health issue(Cummings and Melton, 2002).

The incidence of osteoporotic fractures of the wrist and hip have been reported to be as high as 650 and 670 per 100,000 of the Scottish population respectively(Court-Brown et al., 2006, Court-Brown and Caesar, 2006), and for Caucasian women, there is a one-in-six lifetime risk of sustaining a hip fracture, greater than the one-in-nine lifetime risk of developing breast cancer(Cummings and Melton, 2002). One in three women and one in twelve men over the age of 50 will suffer an osteoporotic fracture, affecting around 200,000 women and 40,000 men in Scotland(SIGN, 2003). Hip fractures alone have been reported to account for over 20% of orthopaedic bed days(SIGN, 2003). The total cost to the NHS of osteoporotic fractures is estimated to be as high as £1.7 billion per year(Torgerson and Bell-Syer, 2001).

The current definition of osteoporosis as provided by the World Health Organisation is a bone mineral density (BMD) or bone mineral content (BMC) value less than two and half standard deviations below the young adult average value i.e. a T score of less than -2.5(WHO, 1994). Osteopenia is defined as a BMD or BMC value less than one standard deviation below but not less than two and a half standard deviations below the young adult average i.e. a T score less than -1.0 but greater than -2.5(WHO, 1994).
The standard method for assessing bone mineral density is Dual Energy X-ray Absorptiometry (DXA), as recommended by the SIGN Guidelines (SIGN, 2003). This provides a measure of bone mineral density at the hip and spine (Ramachandran, 2006), allowing for the diagnosis of osteoporosis or osteopenia (WHO, 1994). (This is discussed in more detail in section 2.61). Diagnosis of Osteoporosis in the general population is an important public health measure as this can allow Primary Care Physicians to provide primary and secondary prevention measures to limit the progress of osteoporosis and so reduce the risk of fragility fractures (SIGN, 2003). Such treatments are dependent on the extent of the osteoporosis with management directed by the national SIGN Guidelines on Management of Osteoporosis (SIGN, 2003).

However, in the field of Orthopaedic Surgery, diagnosis of osteoporosis or rather the quantification of the degree of osteoporosis in patients who have sustained osteoporotic fracture and require surgical intervention has separate implications (Huber et al., 2009). These relate to the field of fracture fixation, in which the quality of bone can influence the success and thus choice of material and methods used for fixation (Huber et al., 2009, Gundle et al., 1995, Tingart et al., 2006, Barrios et al., 1993, Krappinger et al., 2011). For instance, with osteoporotic fractures of the distal radius, surgeons are advised against using K-Wire Fixation as a method of fracture stabilisation, as the K-Wires have a high risk of ‘cut-out’ failure in the osteoporotic bone (Court-Brown et al., 2006). However, methods available for pre-operative assessment of bone mineral density are limited, and often rely on qualitative assessments of pre-operative radiographs, which have shown to be inaccurate (Huber et al., 2009), and as such have been formally dissuaded by the SIGN Guidelines (SIGN, 2003). In most instances however, these are the only imaging resource available for patients pre-operatively (Huber et al., 2009), even though, a quantitative assessment of bone mineral density from pre-operative radiographs (Huber et al., 2009) would be useful.
2.2 The Biochemistry and Physiology of Bone

Bone is a lightweight, semi-rigid, dense, porous, calcified connective tissue which forms the major portion of the human skeleton (Ramachandran, 2006). It is a composite material consisting of cells (10 per cent) within a matrix (90 per cent) that has an inorganic and organic component (Ramachandran, 2006). Further to this, water comprises around a fifth the volume of living bone (Ramachandran, 2006). The cell population comprises osteoblasts (bone-forming cells) and osteoclasts (bone-resorbing cells) (Ramachandran, 2006). The dense organic matrix is composed mainly of type 1 collagen fibres along with bone specific proteoglycans, osteocalcin, osteonectin, osteopontin, bone sialoprotein, growth factors and cytokines (Ramachandran, 2006). The collagen present in the organic matrix provides bone with tensile strength, which offers resistance to fracture (Ramachandran, 2006). The inorganic component of the matrix is largely composed of mineral, chiefly calcium phosphate (in the form calcium hydroxyapatite) and calcium carbonate (Ramachandran, 2006). This component gives bones its rigidity, with a high compressive strength, but poor tensile strength and very low shear stress strength (Ramachandran, 2006). The composite structure of bone creates a material that is both resistant to compression and resistant to tension (Ramachandran, 2006).

2.21 Cortical and Cancellous Bone

Within mature (lamellar) bone in the adult human, there are two different types of bone tissue - cortical (compact) and cancellous (trabecular) bone (Ramachandran, 2006). A single bone is composed of varying amounts of these two types of bone which have different mechanical behaviours (Ramachandran, 2006). With age, these types of bone tissue change in proportion and microstructure, and so the mechanical properties vary accordingly (Ramachandran, 2006).

Cortical bone comprises 80 per cent of the adult skeleton, forming the surface and diaphyses of long bones and the envelope of cuboid bones (Ramachandran, 2006). Microscopically, it is composed of multiple lamellae which form tubular lamellar systems called osteons or Haversian systems, approximately 50 micrometres in
diameter (Ramachandran, 2006). These osteons are aligned along lines of force and are usually parallel with the long axis of the bone (Ramachandran, 2006). Each osteon has a central neurovascular channel (Haversian canal) surrounded by five to seven lamellae of bone matrix (Ramachandran, 2006). Circles of fixed osteocytes intercommunicate via gap junctions within channels called canaliculi, and these radiate out from the central canal (Ramachandran, 2006). A second system of canals called Volkmann’s canal travel perpendicular to the long bone axis, connecting the inner and outer surfaces of the bone and carrying blood vessels to and from the Haversian systems (Ramachandran, 2006). Compared to cancellous bone, this type of bone is denser, more elastic and more resistant to bending and torsion (Ramachandran, 2006).

Cancellous bone is located in the metaphyses and epiphyses of long bones and in the centre of cuboid bones (Ramachandran, 2006). It is formed by a three-dimensional lattice of interconnecting trabeculae, aligned along axes of mechanical stress, enclosing elements of the bone marrow (Ramachandran, 2006). Each trabeculae is made up of parallel sheets of lamellae (Ramachandran, 2006). Despite an absence of the Haversian system, osteocytes, lacunae and canaliculi in cancellous bone resemble those in cortical bone (Ramachandran, 2006). Due to its larger surface area, cancellous bone has eight times the metabolic turnover rate of cortical bone (Ramachandran, 2006). Within the human skeleton regions of cancellous bone are less dense, less elastic, less brittle and less strong than regions of cortical bone (Ramachandran, 2006).

2.22 The Function of Bone
The composite structure of bone allows it to perform a number of functions which include protection of the internal organs and provision of structural support against which structures of the musculoskeletal system (skeletal muscles, tendons and ligaments) can attach to. The bones can they act as levers to provide motion (Ramachandran, 2006). Other functions of bone include production of blood
cells, acid base function, storage of growth factors and fat, and an endocrine role in phosphate, glucose and fat homeostasis (Ramachandran, 2006).

Lastly the bony skeleton provides the major proportion of the calcium reservoir in the human body, accounting for over 99% of this (Ramachandran, 2006). This reservoir is dependent on calcium intake and deposition, and removal is influenced by a number of factors including Parathyroid hormone (PTH) and Vitamin D (Ramachandran, 2006). Bone metabolism is also influenced by the load applied across the bone as a structure (Ramachandran, 2006). Formation of new bone is a dynamic process, under the influence of muscular activity and hormonal factors, and is counterbalanced by the resorption of bone (Ramachandran, 2006). The equilibrium is dependent on osteoblastic and osteoclastic activity (Ramachandran, 2006).

The ageing process results in a net loss of bone mass (i.e. loss of mineral per unit volume), together with microarchitectural deterioration, changing the mechanical properties of bone (Stromsoe, 2004). It reflects an imbalance between deposition and removal of calcium, with a resultant thinning of cortical bone and reduction of trabeculae in cancellous bone (Stromsoe, 2004). The organic matrix, chemical composition, and the histological pattern of bone remain unchanged. (Stromsoe, 2004). When this process advances to a significant level, it is termed osteoporosis (Stromsoe, 2004).

2.3 Osteoporosis

Osteoporosis is a systemic disease characterised by loss of bone mass and microarchitectural deterioration of bone tissue, with a consequent increase in bone fragility and susceptibility to fracture risk (Consensus_Development_Conference, 1993).

Bone mass increases during skeletal growth to reach a peak between age 20 to 40 years but falls thereafter (Colledge et al., 2010). The increase and subsequent reduction is controlled by genetic and environmental factors, with genetic factors accounting for 80% of population variance in peak bone mass (Colledge et al., 2010).
Polymorphisms in various genes have been found to alter vitamin D receptors, collagen type 1 receptors and oestrogen receptors and as such alter peak bone mass and subsequent loss (Colledge et al., 2010). Environmental factors such as exercise and calcium intake during growth and adolescence are important in influencing peak bone mass and bone loss (Colledge et al., 2010). When the process of net bone loss exceeds a certain critical level, then the patient is defined as suffering from osteoporosis (Colledge et al., 2010).

Osteoporosis can either be primary or secondary (Stromsoe, 2004). Primary forms include idiopathic osteoporosis (early-onset with no underlying cause), type I (the postmenopausal form, characterised by deterioration in cancellous bone density) and type II (the senile form, characterised by decreased cortical thickness of long bones) (Stromsoe, 2004). Secondary osteoporosis occurs due to external factors, such as medication (e.g. corticosteroids), or due to endocrine diseases (e.g. Cushing’s Disease) (Stromsoe, 2004).

The World Health Organization (WHO) has established diagnostic criteria for osteoporosis based on the measurement of BMD, expressed as the T-score, which is the number of SD below the mean BMD of young adults at their peak bone mass (WHO, 1994). Osteoporosis is defined as a T-score of −2.5 SD or below. Established (severe) osteoporosis is defined as T-score of −2.5 SD or below with one or more associated fractures (WHO, 1994).

More than two million women have osteoporosis in England and Wales (NICE, 2008). The highest incidence is found in older white women, with the prevalence of osteoporosis rising from 2% at 50 years to more than 25% at 80 years (NICE, 2008). Risk factors for osteoporosis include low body mass index, untreated premature menopause, prolonged immobility, medications such as corticosteroids and certain medical conditions such as ankylosing spondylitis and Crohn’s disease (NICE, 2008).

The clinically apparent and relevant outcomes of osteoporosis are fractures (NICE, 2008). Such fractures are termed ‘fragility’ fractures, sustained as the result of low-
trauma, a force equivalent to a fall from standing height (NICE, 2008). These occur most commonly in the vertebrae, hip and wrist, and result in substantial disability, pain and diminished quality of life (NICE, 2008).

Clinical factors associated with increased fracture risk include increasing age and low BMD, previous fragility fracture, parental history of hip fracture, excess alcohol intake, long-term systemic use of corticosteroids and rheumatoid arthritis.

2.4 The Epidemiology of Osteoporotic Fractures

In England and Wales, there are an estimated 180,000 osteoporosis-related symptomatic fractures annually, of which 70,000 are hip fractures, 25,000 are clinical vertebral fractures, and 41,000 are wrist fractures (NICE, 2008). In Scotland there are over 20,000 cases of osteoporotic fractures annually (SIGN, 2003), with the incidence of osteoporotic fractures of the wrist and hip reported as 650 and 670 per 100,000 of the Scottish population respectively (Court-Brown et al., 2006, Court-Brown and Caesar, 2006).

Hip fractures alone have been reported to account for over 20% of orthopaedic bed days (SIGN, 2003). The total cost to the NHS of osteoporotic fractures is estimated to be as high as £1.7 billion per year (SIGN, 2003).

In terms of risk, one in three women and one in twelve men over the age of 50 are predicted to suffer a fracture, in Scotland affecting around 200,000 women and 40,000 men (SIGN, 2003). In England and Wales, the lifetime risk of a vertebral fracture, for women aged over 50, is estimated to be one in three, and that of hip fracture, one in five (NICE, 2008). For caucasian women as a whole, there is a one-in-six lifetime risk of sustaining a hip fracture, greater than the one-in-nine lifetime risk of developing breast cancer (Cummings and Melton, 2002).
With an increasing elderly population and an accompanying rise in rates of sedentary lifestyles, the number of patients suffering an osteoporotic fracture in the future is predict to increase markedly(NICE, 2008).

Osteoporotic fractures are an increasingly significant problem and as such optimal management of them is vital in modern healthcare.

2.5 Bone Mineral Density

Bone Mineral Density is defined the amount of mineral matter per unit of bone(Ramachandran, 2006). It is based on the physical measure of density which is the ratio of mass to volume (g/cm$^3$)(Stromsoe, 2004). It encompasses the mineral content of both cortical and cancellous bone, providing a measure of hydroxyapatite per unit volume(Ramachandran, 2006). This provides a proxy measure of bone strength and susceptibility to fracture(Chappard et al., 2010). Loss of bone mineral reflects the loss of bone mass in osteoporosis(Ramachandran, 2006).

In the clinical setting, bone mineral density is largely assessed by two modalities - Dual X-ray Absorptiometry (DXA) and Quantitative Computed Tomography (QCT)(Ramachandran, 2006). Dual X-ray Absorptiometry (DXA) is an absorptiometry technique which provides an ‘‘area density’’ (g/cm$^2$) i.e. the bone mineral contained in a given projected area of the bone(Stromsoe, 2004). In contrast, QCT has the ability to create a measure which is related to the true volumetric density of bone (g/cm$^3$)(Stromsoe, 2004). Although “area” bone mineral density (as per DXA) and true bone mineral density (as per QCT) are different, both produce similar results(Stromsoe, 2004).

The standard sites chosen to measure BMD are the proximal femur and the lumbar vertebrae (L1 to L4 vertebral bodies)(SIGN, 2003). Data from such measures are standardised among the population with results processed as T-Scores and Z-Scores to produce equilibrated figures for interpersonal comparison(WHO, 1994).
The T-score is the number of standard deviations below the mean BMD at the relevant site of the young normal reference mean i.e. that of a healthy thirty year old, which is sex and ethnicity matched (WHO, 1994). This is the relevant measure when screening for osteoporosis and the criteria of the World Health Organization is: a T-score of -1.0 or higher is normal; a T-score between -1.0 and -2.5 is defined as osteopenia; a T-score of -2.5 or lower is defined as osteoporosis (WHO, 1994). T-score measurements vary depending on the site and method of investigation (Ramachandran, 2006). Such measurements of BMD from the hip and spine provided by DXA can estimate fracture risk (WHO, 1994).

The Z-Score for the patient is the number of SD below the mean BMD at the relevant site of a sex, ethnicity and aged matched individual (WHO, 1994). It is usually used in cases of severe osteoporosis i.e. when the T score is less than 2.5 standard deviations below this normal (WHO, 1994). A low Z-score is often an indicator that a coexisting factor is contributing to the osteoporosis such as glucocorticoid therapy, hyperparathyroidism, or alcoholism (Ramachandran, 2006).

Limitations of BMD assessment include: the interference imparted by the soft tissue overlying the bone; results provide a proxy measure for bone strength and fracture risk; reference standards for some populations are unavailable; crushed vertebrae can provide falsely high BMD so must be excluded from analysis (Ramachandran, 2006).

2.6 The Standard Measurement of Bone Mineral Density

2.61 Dual X-Ray Absorptiometry
The gold standard assessment for BMD is DXA, providing an integral measurement of both cortical and cancellous bone (SIGN, 2003). This is the most widely used and most thoroughly studied bone density measurement technology (SIGN, 2003).

The DXA technique is based a process by which an X-ray source produces two X-ray beams, each of different energy levels (Ramachandran, 2006). The amount of X-rays that pass through the bone is measured for each beam, with allowances for
thickness of bone examined, and surrounding soft tissue through which it travels (Ramachandran, 2006). By assessing the differential absorptiometry between the two beams, an area density of the bone can be measured (Ramachandran, 2006).

A DXA scan takes 10 to 20 minutes to complete. It is a painless, non-invasive procedure and provides a near negligible exposure to radiation (SIGN, 2003). The cost per DXA scan is around £30, providing a cost efficient service for the diagnosis and monitoring of osteoporosis (SIGN, 2003).

A standard DXA scan will comprise BMD assessment of the hip and spine: in certain situations, BMD can be measured at the forearm (SIGN, 2003). DXA estimates of BMD differ between sites around the body, with moderate to good correlations for BMD at different sites (Cummings et al., 1993). BMD of a specific site is the best predictor of fracture at that site (Clowes et al., 2005). DXA results offer a reliable method for the diagnosis of osteoporosis and also act as a method of evaluation of the effect of medical treatments on BMD in clinical trials (SIGN, 2003).

In Scotland, patients are enrolled for DXA scanning if they have sustained a fragility fracture (proximal femur, distal radius, vertebra wedge compression) over the age of 55 or if they have suffered a low impact fracture at an age below this (SIGN, 2003). Other indications for referral include X-ray evidence of osteopenia, family history of osteoporosis, height loss greater than 5 cm, prolonged amenorrhoea and prolonged corticosteroid use (SIGN, 2003).

Depending of the value of the DXA score, management includes lifestyle advice and measures to reduce falls, first line medications such as vitamin D and calcium and second line medications such as bisphosphonates, selective oestrogen receptor modulators and hormone replacement therapy (SIGN, 2003).
2.62 Other Methods of Bone Mineral Density Assessment

Other validated BMD assessment techniques include Quantitative Computed Tomography (QCT), Peripheral Dual-energy X-ray Absorptiometry and Single-energy X-ray Absorptiometry and Quantitative Ultrasound (Ramachandran, 2006).

QCT is widely used to measure BMD particularly that of the spine (Ramachandran, 2006). It can be obtained from a normal CT Scanner if additional software is purchased (Ramachandran, 2006). It assesses the attenuation of X-ray beams by a number of vertebral bodies in Hounsfield units and compares this against a reference standard of different concentrations of hydroxyapatite in a reference model scanned simultaneously (Ramachandran, 2006). Hounsfield units are converted to bone equivalent values (g/cm³ of hydroxyapatite) (Ramachandran, 2006). This provides a true density estimate, as opposed to DXA which provides an area density (Stromsoe, 2004). It allows differentiation between cortical and cancellous bone (Stromsoe, 2004). This allows a more accurate estimation of BMD and bone strength in diaphyseal regions of bone, however, in the metaphyseal regions i.e. proximal femur, DXA provides a similarly accurate measure of BMD and bone strength (Stromsoe, 2004). The drawback of QCT is the high radiation dose, the cost and limited availability with competing demands for CT scanners (SIGN, 2003). As such, SIGN Guidelines advocate against the use of QCT for routine diagnosis or monitoring of osteoporosis in NHS Scotland (SIGN, 2003).

Other methods such as Peripheral DXA and Single X-ray Absorptiometry are used: as screening methods for subsequent DXA; for diagnosis of osteoporosis; or the monitoring of treatment (SIGN, 2003). Their advantages compared to DXA include decreased cost and portability of equipment (SIGN, 2003). However, there is limited evidence to validate these techniques against the current standard of DXA, with only a moderate correlation between peripheral and axial BMD (Clowes et al., 2005, Stone et al., 2003). As such, SIGN advise against the use of such modalities in the diagnosis, management and monitoring of osteoporosis (SIGN, 2003).

Quantitative ultrasound (QUS) has also been suggested as a possible alternative to assess bone quality (Ramachandran, 2006). This non-invasive peripheral technique, performed at the calcaneus, tibia, or phalanges, assesses ultrasound velocity and
attenuation at the affected area, to provide a measure of bone quality (Ramachandran, 2006). Its advantages include no radiation exposure and portability of equipment (Ramachandran, 2006). However there is considerable variation both between operators and between equipment, with questionable precision (SIGN, 2003). Thus comparison against population and age-matched subjects is difficult, limiting its applicability (SIGN, 2003). As such SIGN advises against use of QUS for investigation, management or monitoring of osteoporosis (SIGN, 2003).

Thus despite a number of alternatives, DXA remains the Gold Standard Modality of BMD assessment (SIGN, 2003).

2.7 Requirement for Pre-Operative Measurement of Bone Mineral Density

This BMD assessment is carried out on an elective basis, due to availability and location of resources (SIGN, 2003). As such while DXA assessment can be used for post-operative diagnosis of osteoporosis, it is difficult to employ this for pre-operative assessment of BMD. Such pre-operative assessment of bone quality however could provide very useful information to surgeons in order to allow them to choose the optimal equipment for fracture fixation (Huber et al., 2009).

As comparison, in the field of Engineering, when creating a product to provide structural integrity, much investment goes into the assessment of the product’s stress, strain and fatigue properties prior to implementation, with specific variations made based on the nature and strength of the material to which it is to fix (Ong and Bouazza-Marouf, 2000). However, despite all the investment and research placed into modern-day orthopaedic fixation implants, little consideration is applied to the individual nature of material they are to fix (i.e. the bone) (Ong and Bouazza-Marouf, 2000). This is in spite of extensive research confirming the key relationship between bone quality and success of anchorage of surgical fixation materials (Court-Brown et al., 2006, Huber et al., 2009, Krappinger et al., 2011, Barrios et al., 1993, Tingart et
al., 2006). This is a major factor in implant-related failure in modern orthopaedic surgery which remains largely unaddressed (Huber et al., 2009).

For example, with fractures of the distal radius that require surgical fixation, there are a number of techniques available. These include Kirschner Wire fixation of the fracture segments, plating across the fracture with screw fixation or external fixation of the fracture (Court-Brown et al., 2006). In such cases, the biomechanical strength and quality of the bone plays a crucial role in the stability of the constructs used for fixation (Court-Brown et al., 2006). In the case of Kirschner Wire fixation, several authors have advised against its use to stabilise osteoporotic bone due to the high possibility of ‘cut-out’ failure (Court-Brown et al., 2006, Azzopardi et al., 2005, McQueen, 1998, Stoffelen and Broos, 1999). To note, wires of the same diameter which are placed under tension and used in circular external fixator can provide reliable fixation in osteoporotic bone (Donaldson et al., 2012b); however ‘cut-out’ rates are still higher in osteoporotic bone compared to bone of normal BMD (Donaldson et al., 2012a, Donaldson et al., 2012b).

Similarly, at the proximal femur, studies have shown that BMD is correlated with ‘cut-out’ of fixation devices (Huber et al., 2009, Barrios et al., 1993, Gundle et al., 1995) and this can be influenced by material and mode of fixation device (Barrios et al., 1993, Taheri et al., 2011).

However, due to service restriction and due to difficulties posed in achieving the required positioning with hip fracture patients for a sufficient time period to complete a DXA scan, DXA appointments for fragility fracture patients are consistently organised a minimum four to six weeks post-operatively, so such information is not available pre-operatively (SIGN, 2003).

Thus often, the only pre-operative imaging modality of the bone available to the surgeon to make such decisions is plain radiography (Huber et al., 2009). At present, in routine clinical practice, there are no regularly-used validated objective measures on plain radiographs that help surgeons quantify BMD or bone quality from these imaging modalities (Huber et al., 2009). Ongoing qualitative non-validated interpretation of the radiographs remains regular practice (Huber et al., 2009). This,
combined with personal experience and preference, often forms the basis for choice of fixation techniques and materials (Huber et al., 2009). Quantitative tools that allow assessment of BMD and bone quality from plain radiography may, however, provide a more accurate assessment, thus allowing objectively-based decisions on optimal fracture fixation techniques and materials (Huber et al., 2009).

2.8 Current Methods for Pre-Operative Assessment of Bone Mineral Density and Quality

Current methods of pre-operative assessment of BMD and bone quality largely centre on subjective, qualitative assessment of the plain radiograph by the surgeon (Huber et al., 2009). The main method used remains visual assessment of mineralisation grade of the skeleton (Wagner et al., 2005). This is normally performed by assessment of photographic blackening and morphological signs of the bones i.e. changes in the thickness of the cortical layers of long bones and rarefaction of trabecular pattern of cancellous bone (Garton et al., 1994).

Such subjective assessment, even when supplemented by quasi-quantitative measures, is variable, unreliable and strongly influenced by user-experience and interpretation (Wagner et al., 2005, Garton et al., 1994, Koot et al., 1996). The photographic blackening of the radiograph by a bone is dependent not only on the degree of mineralisation but also on the amount and quality of the non-mineralised tissue within and covering the bone (Omnell, 1957). Other factors which cause inaccuracy with this method include the need for a source of radiation of uniform intensity and similar quality over the area of interest (Omnell, 1957, Meema et al., 1964), the variations introduced by non-uniform scatter (Keane et al., 1959) and the variations in film handling and processing (Doyle, 1961).

As such, the SIGN Guidelines advise that plain radiographs should not be used as a measure of osteoporosis (SIGN, 2003). They note that such assessment is open to marked observer variation, and while severe osteopenia on plain films can correlate with low BMD as measured by DXA, it remains unreliable for accurate use (SIGN,
Use of digital radiography and its accompanying tools, has been reported not to offer improved accuracy in this technique (Wagner et al., 2005).

Given the importance of bone quality to the success of anchorage of surgical fixation materials (Huber et al., 2009, Court-Brown et al., 2006, Barrios et al., 1993, Krappinger et al., 2011, Tingart et al., 2006), more objective pre-operative techniques to allow reliable quantitative assessment of such measures must be made available (Huber et al., 2009).


2.81 Cortical Measures

Early attempts to quantify BMD were based on the cortical dimensions of radiographs. Simple cortical measures have been used throughout multiple parts of the body, including the clavicle (Anton, 1969), the humerus (Bloom and Laws, 1970, Tingart et al., 2003, Meema and Meema, 1963), the proximal radius (Meema et al., 1965), the femur (Cooper et al., 1986, Chappard et al., 2010) and the metacarpus (Bloom and Laws, 1970).

Some of the earliest descriptions of this technique come from Meema et al (1965), who performed a prospective observational cohort study, assessing the width of the cortex of the proximal radius diaphysis (distal to the radial tuberosity) in a series of 207 patients, and comparing this to age and gender. They showed that thinning of the proximal radial cortex increased with age with a greater decline seen in females.
compared to males. They also showed that patients with radiological evidence of spinal osteoporosis (i.e. fracture) had lower values of cortical thickness. They also noted there was an increased rate of loss of cortical bone associated with onset of the menopause. While they advocated that this was sensitive marker to bone loss and subsequent osteoporosis, they were unable to provide fixed BMD measures to validate this.

The same authors (Meema and Meema, 1963) showed similar results in another prospective observational cohort study. Assessing the combined cortical thickness of the medial and lateral cortices of the distal humerus in a lateral radiograph of the humerus, they showed this decreased with age, female gender and associated factors of osteoporosis. However, again they were unable to validate this technique against formal BMD measures.

Other early descriptions of this technique include that by Anton et al (1969), who performed a retrospective cohort study, assessing the combined cortical thickness of the upper clavicular cortices on chest radiographs. From a series of 120 patients, they found this measure to decrease with age, female gender and the presence of osteoporotic vertebral fractures, as well as correlate well with the previously validated Osteoporosis Index (Barnett and Nordin, 1960). They stated that a combined cortical measure of 1.5 mm. or less was indicative of osteoporosis. Unfortunately, however, such measures were not validated against formal BMD measures, so such results are of limited value in modern practice.

Bloom and Laws (1970) performed a clinical cohort study assessing the cortical thickness of the distal humerus in 254 caucasian females. They used a cortical summation of the medial and lateral cortices at the most distal point on the diaphysis where the endosteal borders of cortices were parallel to each other. They found that over 95% of their cohort aged 20-39 years had a combined cortical thickness over 7.5 mm, and that after 50 years of age this value fell significantly. They advocated that a value of less than 7.5 mm implied notable deterioration of BMD, signifying approximately a loss of 25% bone mass, as compared to a normal young caucasian
female. Unfortunately, such measures were not validated against BMD measures, again limiting objective evidence of the usefulness of this technique.

Blooms and Laws (1970) also assessed cortical values in both the 2nd and 4th metacarpals and the left radial shaft. The cortical values of the metacarpal were usually half that of the humerus, and so observer errors had proportionately larger effects on the results. As such they recommended use of the humeral cortical measures over other upper limb cortical measures.

More recently, Cooper et al (1986) performed a clinical-based laboratory study, assessing the dry ash weight per volume of 62 femoral head excised during fracture neck of femur surgery and comparing these to the radiological width of the femoral calcar. They found a statistically significant correlation between these, concluding that width of the femoral calcar was a useful tool to assess femoral neck BMD. Again however, this study failed to provide validation of their results against DXA or other similar measures of BMD, limiting its value in current clinical practice.

In contrast to the previous studies, Chappard et al (2010) measured the medial and lateral femoral cortices and the calcar femoral thickness from the proximal femur in digital radiographs and assessed their correlations with DXA BMD measures of the 80 femoral specimens. In this laboratory-based study, they found Pearson correlation coefficients of r=0.76 for the calcar femorale thickness, r=0.58 for the lateral femoral cortex, and r=0.67 for the medial femoral cortices (all significant at P<.0001) against DXA. These geometry values also correlated significantly with propensity to fracture.

Such results provide promising evidence of the value of such measures in predicting bone mineral density from digital radiographs. However, it is important to note that these results were obtained during laboratory conditions, with isolated skeletal samples. As such, this study failed to account for a number of factors, which can influence radiographic assessment in clinical practice, including the effect of the surrounding soft tissue on image quality and the variation observed in image
magnification due to the inconsistent relationship between the patient and the x-ray machine. As such, it remains to be determined if such a technique remains as effective in clinical practice.

2.82 Cortical Ratios

Use of cortical measures alone fails to account for variations in bone geometry, and as such it has been suggested that these measures could have improved accuracy when utilised in a ratio (Barnett and Nordin, 1960).

Such ratios include the Cortical Index which is the ratio of the sum of the medial and lateral cortical thicknesses to the total diameter of the diaphysis at the level of maximum cortical thickness (Barnett and Nordin, 1960). This has been used for a variety of locations including the femur, humerus and metacarpus (Barnett and Nordin, 1960, Virtama and Telkka, 1962).

Use of such ratios was first described by Barnett and Nordin, 1960. In a retrospective case control study, they compared radiographs of the femur and hand of 150 patients with suspected osteoporosis to 125 ‘normal’ controls, calculating femoral and metacarpal cortical indices for both cohorts. They found that the control group had significantly higher scores that the ‘suspected osteoporosis’ group. The lack of validation against BMD measures was a considerable shortcoming in this study; however this technique proved an early successful attempt to estimate BMD from plain radiography.

The shortcomings from above were addressed by Virtama and Telkka, 1962. In a laboratory based study, they measured the cortical indices of 47 cadaver femora and 38 cadaver humeri and then compared these to the dry ash weight per volume of the bones. They found statistically significant correlations for both cohorts and concluded that the cortical index could provide an easy-obtainable, objective measure of BMD.
Further assessment of this technique was performed by Wishart et al, 1993. In a clinical control study, they measured the cortical indices of the 2\textsuperscript{nd} metacarpal in the right hand of 239 post-menopausal women and found that this measure showed significant correlations with forearm BMD from single photon absorptiometry and vertebral BMD from single energy computed quantitative tomography. Similarly assessing the cohort by those who had suffered fractures and those who had not, they found the fracture cohort had significantly lower cortical indices as well as significantly lower BMD scores. They suggested that the metacarpal cortical index could be used as a low cost measure of BMD and fracture risk.

Again, while these latter two studies show encouraging results, both fail to show correlations with DXA BMD values, the currently used technique of BMD assessment in clinical practice(SIGN, 2003). However both provide strong correlation data with validated BMD measures suggesting this technique can provide clinically useful measures of BMD.

2.83 Combined Cortical Measures

While these studies assess measures at one region of the bone, newer methods are encompassing measures at a number of sites, in an attempt to provide an improved estimation of the BMD(Tingart et al., 2003).

Tingart et al. (2003) assessed BMD at the proximal humerus by calculating the mean of four measures (two medial and two lateral) of the proximal cortex of the humeral diaphysis. (Level 1 was the most proximal level of the humeral diaphysis where the endosteal borders of the lateral and medial cortices were parallel to each other: Level 2 was 20 mm distal to level 1.) A laboratory based study with 19 human cadaver humeri, cortical measures were assessed from both cadaver dissection and plain radiographs, and comparisons were made with DXA measures. The four-point combined measure was found to be significantly correlated with BMD at several regions of the proximal humerus. These findings suggest that combined measures of cortical thickness can provide reliable measures of BMD.
2.84 Simple Textural Measures

Other quantitative methods for radiographic assessment of BMD include simple texture analyses of radiographs.

This method was introduced by Singh et al (1970) who created an index for radiographic analysis of osteoporotic changes at the proximal femur (see Figure 2.1).

Figure 2.1: The Six Gradings of the Singh Index (Singh et al., 1970).

This was a six part classification which graded the presence, quantity and location of the compressive and tensile bone trabeculae in the proximal femur (Singh et al., 1970). The study was performed as case control study, comparing the Singh Index from AP Pelvic Radiographs to the Beck and Nordin Histological Grading of Osteoporosis from iliac crest bone samples from the same patients. The Singh Index
correlated well with the Beck and Nordin Histological Gradings, showing that progressive loss of the trabeculae of the proximal femur occurred as the bone deteriorates to severe osteoporosis. This suggested that the Singh Index could be used as a radiological scale for the diagnosis and grading of osteoporosis.

Use of this Index was further validated by Cooper et al (1986). In a clinical-based laboratory study, they assessing the dry ash weight per volume of 62 femoral head excised at fracture neck of femur surgery and compared these to the pre-operative Singh Grading of the proximal femurs. They found a statistically significant correlation and so concluded that this radiological measure was a useful tool to assess femoral neck bone mineral density.

However, Koot et al. (1996) studied the interobserver and intraobserver reliability of the Singh Index, from six observers in a series of 80 patients, as well as its correlation with DXA BMD results. Interobserver reliability was poor, as was correlation with DXA results. In order to improve the applicability of the Index, the authors grouped the results into three categories (A – I and II, B – III and IV, C – V and VI). However this also showed poor interobserver reliability and poor correlation with DXA. As such the authors advised against use of this technique as a measure of BMD.

Similar measures of textural analysis have been used in the Calcaneus to form the Calcaneal Index akin to Singh Index(Jhamaria et al., 1983, Aggarwal et al., 1986). As in the proximal femur, this assesses the presence of primary and secondary compressive and tensile trabeculae. Studies have shown this Index to correlate well with age and gender, but no clear data exists regarding reliability or correlation with BMD measures(Jhamaria et al., 1983, Aggarwal et al., 1986).

It would appear that textural measures on radiographs are yet to be validated as a reliable tool with which to predict BMD. While they show correlations with proxy measures of osteoporosis, they fail to show consistent significant correlations with BMD measures.
2.85 Complex Textural Measures

More complicated texture analysis models on plain and digital radiographs have been developed and applied throughout the body, including the proximal femur (Chappard et al., 2010, Huber et al., 2009, Gregory et al., 2004, Lee et al., 2002, Pulkkinen et al., 2008), the distal radius (Majumdar et al., 2000), the vertebrae (Caligiuri et al., 1994) and the calcaneus (Benhamou et al., 2001, Chappard et al., 2005, Lespessailles et al., 2007).

These involve either analysis of degree of bone anisotropy with Fourier Analysis (Majumdar et al., 2000, Gregory et al., 2004, Caligiuri et al., 1994, Benhamou et al., 2001, Chappard et al., 2005) and Principle Component Analysis (Gregory et al., 2004) or analysis of radiographic radiation density with Co-Occurrence Matrices (Huber et al., 2009, Chappard et al., 2010, Lee et al., 2002, Pulkkinen et al., 2008, Lespessailles et al., 2007). These methods assess the density, frequency and orientation of the bone trabeculae, as a proxy-method of assessing density of bone structure and as such BMD and bone quality.

While the results of these methods have shown statistically significant correlations with BMD (Huber et al., 2009, Chappard et al., 2010, Majumdar et al., 2000, Pulkkinen et al., 2008) propensity to fracture (Gregory et al., 2004, Chappard et al., 2005) and forces requires to displace fixation materials (Huber et al., 2009), the analysis techniques are often not well understood by medical technicians so interpretation of results can be complicated (Huber et al., 2009, Chappard et al., 2010). Similarly the software for such analyses is not readily available and as such, integration into radiological imaging programmes used in current medical practice is not a reality currently. If this were possible, these methods could provide very useful information, but, unfortunately, currently they are restricted to experimental use.

2.86 Aluminium Equivalent Measures in Plain Radiography

The use of an aluminium step wedge in plain radiography to correlate aluminium equivalent measures with BMD is a long-established (Colbert et al., 1967, Beyer-

The step wedge is used as a calibration device in the radiograph to provide a relationship between optical density (i.e. grey value) and equivalent Aluminium thickness (AEq), normalising radiographs between different patients(Dawson, 2009). As such it can be used to obtain equivalent measures for BMD.

One of the early descriptions of this technique was that by Colbert et al. (1967). They included an aluminium step wedge in plain radiographs of bone, and scanned the images with a microdensitometer to yield optical density, which was then modelled using the exponential Lambert-Beer law to assess the intensity of X-rays hitting the film. A modified first order polynomial equation of the logarithmic relationship was employed to provide a calibration relationship between optical density in the radiograph and equivalent Aluminium thickness. This technique was limited by its requirement for use of a pure aluminium in the step wedge as well as the assumption of use of a monochromatic X-ray beam(Nomoto et al., 2008, de Josselin de Jong and ten Bosch, 1985). Advances in the calibration technique with use of a logarithmic model has accounted for these limitations(Carvalho-Junior et al., 2007, Watts and McCabe, 1999).

The most common reported use of this technique is in the field of dentistry, as a tool to compare the density of intra-oral restorative materials against surrounding anatomical structures(Beyer-Olsen and Orstavik, 1981, Bloxom and Manson-Hing, 1986, Willems et al., 1991).

Beyer-Olsen and Orstavik (1981) published a standardised and reproducible method for radio-opacity assessment of dental materials using an aluminium step wedge for the density analysis of forty root canal sealers. Compared against this technique, visual estimation of such densities was found to lack accuracy and reliability. Bloxom and Manson-Hing (1986) validated the use of an aluminium step wedge in
radiographs as a quality assurance test to assess eighteen machine and film-processing variables as well as various density measures of dental materials. Compared against sensitometric methods employed by electronic medical radiography, they found that use of the aluminium equivalent measures was an accurate method that could be used as an acceptable substitute for this technique. Willems et al (1991) found that a 99.5% pure aluminium step wedge served as a valid reference for evaluating the radio-opacity of 55 composite dental materials, and comparing these to samples of human enamel and dentine of equivalent thickness. Use of the wedge allowed accurate determination between the various samples and so the authors advocated its use in clinical practice.


The technique has also been validated for the assessment of mandibular BMD (Nackaerts et al., 2007). In a laboratory based study, Nackaerts et al. (2007) included an aluminium step wedge in radiographs of thirty-two dried bone cadaveric mandibles. User-led electronic programme analysis of the radiographs found aluminium equivalent measures of mandibular BMD correlated well with DXA measures. Despite the strictly uniform radiograph set-up and processing conditions, aluminium equivalent values correlated markedly stronger with DXA than unprocessed Grey Values, further validating its use in this field.

Other validated uses of aluminium equivalent measures are in the field of archaeology, as a means to estimate BMD of archaeological fossils (Symmons, 2004). Symmons (2004) assessed aluminium equivalent measures of the archaeological
animal bones, via electronic programming, and compared the results to formal volumetric bone density measures and DXA measures. Normalisation for the thickness of the bone in the orthogonal view and correction for magnification and image distortion effects were performed. They found statistically significant correlations between aluminium equivalent measures and density measures, and so advocated the use of the technique in this field.

Despite these encouraging results, the use of this technique to estimate BMD from plain radiographs of the hip and wrist in humans has been limited, due to difficulties in accounting for the attenuation effects of soft tissue, and normalising for variations due to scatter, magnification and step wedge placement (Dawson, 2009).

2.87 Aluminium Equivalent Measures in Digital Radiography
The widespread introduction of digital radiography has however provided further difficulties with utilisation of this technique. Despite the elimination of some of the previous sources of inaccuracy including film development and digitiser response curves, the Automatic Gain Control image processing, that occurs with digital radiography, has been show to skew the Grey Value to Incident Radiation Dose relationship, resulting in significant distortion of any calibration curve between Grey Level and Aluminium Equivalent (Nomoto et al., 2008).

Limited research has been performed into aluminium equivalent measuring in digital radiography. Nomoto et al. (2008) and Carvalho-Junior et al. (2007) noted that despite thorough protocols by the International Organisation for Standardisation (ISO) and American Dental Association (ADA) for aluminium equivalent evaluations in plain radiography, limited evidence exists validating the use of such techniques with digital radiography systems. They advised re-evaluation of existing techniques before applying these to digital radiography, particularly in view of the new processing features and their effects on apparent optical density. Despite such caution, Gu et al. (2006) employed the standard recommended ‘dental’ method to assess the radiopacity of dental materials, i.e. conversion of grey level into
absorbance followed by comparison with aluminium equivalent measures in digital radiography. They found the method precise and repeatable with no statistical difference between measurements of the same materials taken with different exposure settings and at different times (Gu et al., 2006).

Further to this, Nackaerts et al. (2007) measured standard aluminium equivalent values to assess BMD in digital radiographs of 47 human mandibles. Aluminium equivalent measures were found to correlate strongly with both direct volumetric measurements as well as DXA, with good intraobserver and interobserver reliability results. These aluminium measures also provided superior correlation with DXA results than directly assessed grey levels. As such, the authors recommended use of this technique in current practice (Nackaerts et al., 2007).

Despite these promising results, the literature available to validate this technique as a correlate for in vivo BMD measurement in human peripheries is limited (Dawson, 2009). This is due to the substantial effect of soft tissue attenuation on the process (Dawson, 2009). The only study with potential for comparison is that by Kolbeck et al. (1999) which employed aluminium equivalent measures to assess changes of BMD during tibial osteogenesis following tibial-lengthening in pigs. In a cohort of 24 mature female Yucatan pigs, digital radiography was performed over a 10-day consolidation period following tibial distraction ostogenesis, with an aluminium step wedge placed in all images, as a reference to quantify density of regenerate bone. They found their method useful and sensitive in assessing healing progress with a statistically significant correlation between equivalent Aluminium thickness and torsional stiffness. This was despite several shortcomings including failure to correlate aluminium equivalent measures with the logarithmic values of the Grey readings, failure to de-activate the automatic image processing system, failure to account for the effects of soft tissue attenuation, failure to normalise equivalent measures with bone thickness and failure to account for scatter contribution (Dawson, 2009). This likely explains the considerable variation seen in their results (Kolbeck et al., 1999).
When the automatic image processing system was appropriately disabled however, more reproducible correlations between material density and aluminium equivalent values were found (Nomoto et al., 2008).

Nomoto et al. (2008) investigated the accuracy of digital radiography to perform X-ray calibration with an aluminium wedge step, when assessing radio-opacity of dental resins. They compared conventional radiography to digital radiography, both with and without Automatic Gain Control image processing, measuring Aluminium equivalent densities of various substances. It was found that digital imaging with no processing provided the lowest variation in density measurements. They cautioned that the use of Automatic Gain Control image processing in digital imaging caused distortion of the expected step thickness versus grey level relationship, rendering this method unreliable and inaccurate.

Despite these promising results, the successful implementation of such a technique in humans remains guarded by various complicating factors including the effects of soft tissue attenuation and scatter contributions as well as the effects of variations in patient and step wedge placement (Dawson, 2009).

These shortcomings have been addressed within a recent PhD Thesis at our institution (Dawson, 2009).

From this, a robust technical method has been proposed for the acquisition of aluminium equivalent measures from human samples in clinical practice, encompassing various factors such as the optimal design of the aluminium step wedge, the required positioning of the step wedge with regards to the patient, the appropriate imaging required to assess the equivalent measures adequately and the validated process of digital image acquisition and analysis. Various equations have been developed to allow the effects of soft tissue attenuation to be appropriately accounted for as well as to allow for scatter contribution and the heel effect to be appropriately neutralised (Dawson, 2009). With this, an appropriate calibration
method can be achieved between aluminium step thickness and grey level, allowing for aluminium equivalent measures of bone to be calculated in clinical practice.

Using this modified technique, the BMD of the distal radius in a small cohort of distal radial fracture patients was assessed during fracture healing, in the thesis (Dawson, 2009). The study found that the aluminium equivalent measures of the bone increased across the fracture site during healing, in keeping with the increase in BMD one would expect to see during fracture healing (Dawson, 2009). However, the sample size was only four and validation with DXA results was not performed (Dawson, 2009). As such, this technique still requires clinical validation.

2.10 Summary

Osteoporosis and subsequent fragility fractures remain a major problem within current health systems. While assessment and management of osteoporosis remains an effective, well validated process, pre-operative assessment of the fractured osteoporotic skeleton to allow optimal choice of fixation materials remains poorly investigated. Within current practice, such pre-operative assessment is limited to analysis of radiographs. Various methods have been suggested for such assessment including cortical measures and ratios, textural analyses and aluminium equivalent measures. While techniques have been validated in plain radiography, limited evidence is available for use of these techniques in digital radiography. If such techniques were found to provide accurate pre-operative measures of BMD, this could revolutionise the field of fracture fixation materials, allowing these to be custom designed and selected based on the quality of bone they are to stabilise.
Part III

Methods

Study Recruitment and Protocols
Study Recruitment and Protocols

Recruitment of Patients

This section describes the process of patient identification and recruitment for the study, both for the hip fracture patients and the wrist fractures patients. It details the full patient pathway and relevant interventions throughout the study process.
3.1 The Hip Fracture Patients

Study Group

Patients recruited for this section of the study were those with hip fractures in NHS Lothian over the time period September 2011 to August 2012.

In order to achieve this, all patients presenting to the Royal Infirmary of Edinburgh with suspected Hip Fractures (i.e. Proximal Femoral Fractures) from September 2011 to August 2012 were considered as potential study candidates. As per normal practice, those patients were admitted into the care of NHS Lothian via the Emergency Department at the Royal Infirmary of Edinburgh.

Inclusion Criteria

The Principal Inclusion Criteria for this part of the study were:

1. Patients with a suspected isolated hip fracture (i.e. proximal femoral fracture) who presented to the Emergency Department, Royal Infirmary of Edinburgh from September 2011 to August 2012.

2. Patients who were permanent residents within the Lothian Population and who will likely be considered for routine DXA investigation follow-up as part of the Lothian Osteoporosis Service.

Exclusion Criteria

The Principal Exclusion Criteria for this part of the study were:

1. Patients with significant other injuries in addition to their hip fracture.

2. Patients with significant cognitive impairment who were unlikely to be enlisted for further DXA investigation.

3. Patients who for any other reason were likely to fail to meet the criteria for further DXA Investigation following their hip fracture.
4. Patients with pathological fractures

Study Size

There were 50 patients recruited into the Hip Fracture study over this time period. There were 39 female patients and 11 male patients. The mean age was 81 years (range 59-94 years: SD 9 years)

Thirty-seven of these patients underwent DXA scanning of their contralateral hip, in the post-operative period following their fracture. Of these thirty seven patients, thirty-three had adequate radiographs to allow full cortical measure assessment as detailed below. Thirty-two of these patients had adequate radiographs to allow aluminium equivalent measure analysis. Thirty of these patients had adequate radiograph to allow Singh Index assessment of the uninjured hip.

Hip Aluminium Wedge technique

As standard care, these patients had Antero-Posterior Pelvic Radiographs, Antero-Posterior Hip Radiographs and Lateral Radiographs of the injured hip (see Figure 3.1).
The study protocol involved inclusion of an aluminium step wedge within the patients' Antero-Posterior Hip radiograph. This was placed on a Perspex jig attached onto the side of the patient’s trolley, in order to allow the step wedge to sit upright, and so lie perpendicular to the X-ray Beams (see Figure 3.2).
The step wedge was placed adjacent to hip joint, as close to the patient as possible. This involved no alteration to the X-ray Process. During the lateral radiograph, patients had a stainless steel ball bearing attached on to the side of their injured hip, one hand’s breadth distal to the greater trochanter. This allowed estimation of soft tissue thickness in the lateral radiographs (see Figure 3.3).

The mean voltage used for the radiographs was 71.2kV (range 60-80kV; SD 6.3). The mean amplitude used for the radiographs was 46.5mA (range 16-160mA; SD 30.6).
Figure 3.3: Use of the Ball Bearing: a) Attachment to the thigh; b) Analysis in the radiograph

Given the ease of inclusion of the step wedge and ball bearing in the radiographs, this did not prolong the X-ray process beyond the standard duration.

Regarding ethical approval for inclusion of the step wedge in the radiographs, previous ethical approval had been sought for this by Dawson (2009) in her preceding PhD thesis. The Lothian Research Board concluded that this act did not require formal ethical approval (Dawson, 2009) (See Appendix 1).

All radiographs were taken using the FUJI Electronic System, and were processed and analysed as detailed below.
Protocol

Patients progressed through the usual treatment and rehabilitation plans as per a standard hip fracture patient in Lothian, with referral for DXA assessment following discharge, as per routine NHS Lothian care for management of a fragility fracture. DXA assessment for these patients was carried out as per routine with DXA assessment performed of the contralateral hip (femoral neck, trochanteric, intertrochanteric and whole hip region) as well as of the lumbar spine (L1 to L4 vertebrae). This usually took place between 4 and 6 weeks post fracture. Relevant treatment of osteoporosis was then commenced as per appropriate, depending on the DXA Scan results.

The results from the DXA Scanning were obtained by direct access to the DXA Department Archive, with results being downloaded in an encrypted fashion for future reference.

No further follow-up was required of the patients.

With access to the patients’ radiographs and DXA results, a full dataset was available for analysis, with subsequent results as detailed below.

The Protocol for the Hip Fracture Section of the study is summarised in Figure 3.4.
Figure 3.4: The Hip Fracture Protocol Summary

- **Injury to Hip.**
- **Admission to ED, Royal Infirmary of Edinburgh, for Assessment.**
  - **Routine Hip X-ray Series to Assess Hip Injury with inclusion of Aluminium Step Wedge in X-rays.**
  - **Fracture of the Hip identified and treated.**
  - **X-rays stored electronically to be analysed at the Orthopaedic Engineering Laboratory at a later date. This allows an Aluminium Equivalent Value of the Hip Bone to be calculated from the X-ray.**
  - **Patients at risk of osteoporosis are identified and invited to DXA scanning by Lothian Osteoporosis Service.**
  - The patient undergoes a standard DXA scan with two sites of analysis i.e. the contralateral hip and lumbar spine.
  - **Comparison made between the DXA BMD values of the Hip versus the Cortical Bone Measures of the Hip, the Trabecular Patterns of the Hip and the Aluminium Equivalent Values of the Hip.**
3.2 The Wrist Fracture Patients

Patients recruited for this section of the study were those with Wrist fracture in NHS Lothian over the time period August 2012 to April 2013. In order to achieve this, all patients presenting to the Royal Infirmary of Edinburgh with suspected Wrist (Distal Radial) Fractures from August 2012 to April 2013 were considered as potential study candidates. As per normal practice, those patients were admitted into the care of NHS Lothian via the Emergency Department at the Royal Infirmary of Edinburgh. As standard care, these patients had Postero-Anterior and Lateral Digital Radiographs of their injured wrist (see Figure 3.5).

Inclusion Criteria

The Principal Inclusion Criteria for this part of the study were:

1. Patients with a suspected isolated fracture of the wrist (i.e the distal radius) who presented to the Emergency Department, Royal Infirmary of Edinburgh from August 2012 to April 2013.

2. Patients who were permanent residents within the Lothian Population and who will likely be considered for routine DXA investigation follow-up as part of the Lothian Osteoporosis Service.

Exclusion Criteria

The Principal Exclusion Criteria for this part of the study were:

1. Patients with significant other injuries in addition to their wrist fracture.

2. Patients with significant cognitive impairment who were unlikely to be enlisted for further DXA investigation.
3. Patients who for any other reason were likely to fail to meet the criteria for further DXA Investigation following their wrist fracture.

4. Patients with pathological fractures

Study Group Size
There were 54 patients recruited into the Wrist Fracture study over this time period. There were forty-six female patients and eight male patients. The mean age was 74 years (range 57-95 years: SD 11 years). Twenty-three of these patients underwent routine DXA scanning of their hip and lumbar spine, following their fracture. Only nine of these consented to the additional DXA analysis of the contralateral forearm. All 23 had adequate radiographs to allow full cortical measure assessment and aluminium equivalent measure analysis as detailed below.
Wrist Aluminium wedge X-ray technique

Figure 3.5: a) PA Wrist Radiograph; b) Lateral Wrist Radiograph.

The study protocol involved inclusion of an aluminium step wedge within the patients' Postero-Anterior Wrist Radiograph (see Figure 3.6).
The step wedge was placed adjacent to wrist joint, as close to the patient as possible. This involved no alteration to the X-ray Process. During the lateral radiograph, patients had a stainless steel ball bearing placed adjacent to the forearm, one hand’s width distal to the radiocarpal joint (see Figure 3.7). This allowed estimation of soft tissue thickness in the lateral radiographs.

The mean voltage used for the radiographs was 59.4kV (range 52-60kV; SD 2.0). The mean amplitude used for the radiographs was 2.0mA (range 1.6-2.5mA; SD 0.3).
Figure 3.7: Use of the Ball Bearing: a) Placement at the wrist; b) Analysis in the radiograph.

Given the ease of inclusion of the step wedge and the ball bearing in the radiographs, this did not prolong the X-ray process beyond the standard duration.

Regarding ethical approval for inclusion of the step wedges in the radiographs, previous ethical approval had been sought for this by Dawson (2009) in her preceding PhD thesis. The Lothian Research Board concluded that this act did not require formal ethical approval (Dawson, 2009) (See Appendix 1).

All radiographs were taken using the FUJI Electronic System, and were processed and analysed as detailed below.
Patient Protocol

After x-ray, patients progressed through the usual treatment and rehabilitation plans as per a standard wrist fracture patient in Lothian, with referral for DXA assessment following discharge, as per routine NHS Lothian care for management of a fragility fracture.

In order to allow for comparative analysis between the wrist radiographs and DXA analysis of the forearm, DXA assessment in this section of the study included the addition of a DXA analysis of the uninjured forearm.

Favourable Ethical Opinion was sought and granted for this by the South East Scotland Ethics Committee (see Appendix 2). This additional DXA analysis increased the X-ray exposure to the patient by only 0.05μSv (equivalent to the background radiation dose over 1 day) and prolonged the duration of the DXA assessment by only 5 minutes, so was deemed appropriate for the investigation.

The process to allow for this, included identification of all patients who had had an aluminium step wedge included in their wrist radiographs by the principal study investigator, followed by discussion with the DXA co-ordinators to ascertain which patient were appropriate for the additional DXA scanning. Those patients deemed appropriate for the additional DXA scanning were then contacted by telephone by the principal study investigator to discuss the study and to request if they would consider undergoing the additional site of DXA analysis. If they agreed to this, then the study information pack was posted to their home address. The DXA co-ordinator was also alerted to their willingness to participate in the study. Following this, they were allocated an extended DXA appointment by the DXA co-ordinator to allow for incorporation of the additional DXA analysis. When they arrived at their appointment, if they were still willing to proceed with the study, they were consented by the DXA co-ordinator and proceeded with the full DXA scan: hip (femoral neck, trochanteric, intertrochanteric and whole hip region), lumbar spine (L1 to L4 vertebrae) and contralateral forearm (ultra-distal, mid-distal proximal and whole forearm region). The scan usually took place between 4 and 6 weeks post-fracture. Relevant treatment of osteoporosis was then commenced as per appropriate,
depending on the DXA scan results. The patients were allowed to refuse participation in the study at all stages of the process.

The results from the DXA Scanning were obtained by direct access to the DXA Department Archive, with results being downloaded in an encrypted fashion for future reference.

No further follow-up was required of the patients.

With access to the patients’ radiographs and DXA results, a full dataset was available for analysis, with subsequent results as detailed below.

The Protocol for the Wrist Fracture Section of the study is summarised in Figure 3.8.
Figure 3.8: The Wrist Fracture Protocol Summary

Injury to Wrist.

Admission to ED, Royal Infirmary of Edinburgh, for Assessment.

Routine Wrist X-ray Series to Assess Wrist Injury with inclusion of Aluminium Step Wedge in X-rays.

Fracture of the Wrist identified and treated.

X-rays stored electronically to be analysed at the Orthopaedic Engineering Laboratory at a later date. This allows an Aluminium Equivalent Value of the Wrist Bone to be calculated from the X-ray.

Patients at risk of osteoporosis identified and invited to DXA scanning by Lothian Osteoporosis Service.

The patients who decide to attend for routine DXA scanning are telephoned to be included in the study.

If patient agrees, relevant paperwork is mailed and patients are then given the opportunity to sign their consent form prior to their DXA Scan.

The patient undergoes a DXA scan with three sites of analysis.

Comparison is made between the DXA BMD values of the Wrist Bone and the Hip Bone versus the Cortical Measures of the Forearm Bone and the Aluminium Equivalent Values of the Wrist.
Part IV

The Digital Radiographs – Tools for Analysis and Methods for Quantifying Dimensions on Radiographs
The Digital Radiographs – Tools for Analysis and Methods for Quantifying Dimensions on Radiographs

4.1 The Digital Radiographs:

This section describes the acquisition and processing of digital radiographs, obtained from the Emergency Department of the Royal Infirmary of Edinburgh. This permitted for subsequent analysis of the digital radiographs, assessing for objective measures of bone mineral density with comparison against subsequent DXA measures.

All Radiographs were taken within the Emergency Department, Royal Infirmary of Edinburgh. The FUJI electronic radiograph system was used for all radiographs within the study.

The patient set-up used for the hip and wrist radiographs was that used routinely in clinical practice for diagnostic radiographic imaging of suspected hip and wrist fractures.

The alterations to both the hip and wrist radiographs required for the study have been described in Chapter 3.

Prior to commencement of the study, the principal study investigator had collaborated with the Chief Superintendent Radiographer of the Emergency Department of the Royal Infirmary of Edinburgh, to first gain permission to allow the study to proceed and then to co-ordinate the required technique necessary to achieve optimal imaging and placement of the aluminium step wedge and ball bearing in the radiographs. With the optimal technique established, the Chief Superintendent Radiographer educated a select number of senior radiographers regarding this, and it was these clinicians who performed the step wedge and ball bearing insertion in subsequent radiographs.
The CHI numbers of all patients who had undergone radiographs within the study were entered onto a formatted sheet of A4 paper (see Figure 4.1), along with the date of the study, the mA and the kV used for the study. This sheet was stored in the X-ray Suite of the Emergency Department, within a locked drawer, that could only be accessed by the participating radiographers and the principal study investigator.

**Figure 4.1: The Proforma to record Radiograph Details**

<table>
<thead>
<tr>
<th>Date:</th>
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All radiograph images were initially saved and locked to the FUJI system computers within the X-ray Suite of the Emergency Department. Following this, the radiographs were processed electronically and entered into the Hospital Picture Archiving and Communication System as standard practice. The locking function allowed permanent access to the images on the system, as non-locked stored images are routinely deleted every four weeks.

Access to the FUJI system was obtained by the principal study investigator within the X-ray suite of the Emergency Department, at appropriate times, at the discretion of the Chief Radiographer of the Department.
Following guidance by Mrs Nicola Bates from the Medical Physics Team, Royal Infirmary of Edinburgh, and from Mrs Sarah Dawson, University of Edinburgh, via her PhD Thesis (Dawson, 2009), the appropriate images were accessed accordingly and a set sequence of parameters was chosen from the FUJI menu to disable the Automatic Gain Control of the Digital Processing System.

This sequence involved:

1. Accessing the Gains Control Mode (see Figure 4.2).

![Access to the Gains Control Mode: a) Select the ‘Sensitivity’ Button; b) the Control Panel.](image1)

2. Convert from ‘Sensitivity’ Mode to ‘Linearity’ Mode (see Figure 4.3).

![Conversion to ‘Linearity’ Mode: a) Select the ‘Linearity’ Button; b) ‘Linearity’ Mode.](image2)

This enabled unprocessed images to be downloaded from the FUJI system, and so providing unprocessed radiographs for subsequent MatLab analyses (see Chapters 4.11 and 4.12).
When the radiographs were appropriately conditioned using the FUJI system parameters, they were then downloaded in an anonymous format onto a password-encrypted NHS-approved data-USB-medium for transfer to a Password Encrypted Computer in the University of Edinburgh Orthopaedic Engineering Laboratory for subsequent analysis. The anonymising function was performed automatically by the FUJI radiography system. Patient-identifying Codes were attributed to the radiographs to allow the principal study investigator to identify matched AP / PA and Lateral Radiographs as well as to pair radiographs to subsequent DXA Scans. The University computer had both the MatLab 2013a programme and the Image J 2012 programme installed in it to allow for subsequent analyses of the radiographs.

4.2 The MatLab Programme

This section describes the functions employed by the MatLab Programme to allow for analysis of the digital radiographs.

The digital radiographs were uploaded to the Computer via the USB medium as previously described. These were then uploaded onto the MatLab 2013a programme. A programme, which had been previously created by Dawson (2009), for her PhD, performed analysis of the digital radiographs, calibrating gray levels with measures of aluminium thickness, enabling aluminium equivalent measures of BMD to be formulated (as described in Chapter 4.11). This programme was used to provide aluminium equivalent measures both on the hip radiographs and the wrist radiographs. As described below, this programme was also modified (as described in Chapter 4.12) to correct for attenuation of the incident radiation on the radiographs by the perspex jig included in the hip radiographs.
4.3 The Image J Programme

This section describes the functions employed by the Image J Programme to allow for analysis of the digital radiographs.

The digital radiographs were uploaded to the Computer via the USB medium as previously described. These were then uploaded onto the Image J 2012 programme. The Image J programme allowed for measurement of a number of indices within the radiographs, notably circumference and diameter of femoral head; diaphyseal and cortical widths of the proximal femur; and diaphyseal and cortical widths of the radial diaphysis, ulnar diaphysis and metacarpal diaphyses. This was aided by the linear measuring tool, the circle fitting tool and the brightness and contrast tools. These techniques are detailed below.

4.3.1 Measurement of the Circumference of the Femoral Head on the AP Hip Radiograph

The technique to perform measurement of the circumference of the femoral head on the AP radiograph is as follows:

1. The AP Hip Radiograph was uploaded to the Image J programme (see Figure 4.4).

![Figure 4.4: The AP Hip Radiograph.](image-url)
2. The image was magnified to 400% of its original size.

3. The Femoral Head was centred within the image to ensure its full circumference could be visualised (see Figure 4.5).

![Figure 4.5: The AP Hip Radiograph Magnified to 400% and Centred on the Femoral Head.](image)

4. Brightness and Contrast Measures of the Radiograph were adjusted accordingly to visualise the full circumference of the Femoral Head. (see Figure 4.6)

![Figure 4.6: The AP Hip Radiograph Contrast-Enhanced to fully define the Femoral Head.](image)
5. The circle fitting tool was selected and markers placed along the circumference of the femoral head as able. A minimum of 15 markers were used. (see Figure 4.7)

![Figure 4.7: Use of the Circle Fitting Tool to Outline the Circumference of the Femoral Head on the AP Radiograph.](image)

6. The circumference of the femoral head was then established with the circle fitting function (see Figure 4.8).

![Figure 4.8: Use of the Circle Fitting Tool to Define the Circumference of the Femoral Head on the AP Radiograph.](image)

7. The measure of the femoral circumference was obtained from the results section.

8. The procedure was performed 3 times on the AP radiograph to provide a mean.
4.32 Measurement of the Circumference of the Femoral Head on the Lateral Hip Radiograph

The technique to perform measurement of the circumference of the femoral head on the lateral radiograph is as follows:

1. The Lateral Hip radiograph was uploaded to the Image J programme (see Figure 4.9).

Figure 4.9: The Lateral Hip Radiograph
2. The technique as described in 3.31 was repeated using the Lateral Hip Radiograph (see Figure 4.10 to 4.13).

Figure 4.10: The AP Hip Radiograph Magnified to 400% and Centred on the Femoral Head.

Figure 4.11: The AP Hip Radiograph Contrast-Enhanced to define the Femoral Head fully.

Figure 4.12: Use of the ‘Circle Fitting Tool to Outline the Circumference of the Femoral Head on the Lateral Radiograph.

Figure 4.13: Use of the Circle Fitting Tool to Define the Circumference of the Femoral Head on the Lateral Radiograph.
4.33 Measurement of the Diameter of the Femoral Head on the AP Hip Radiograph

The technique to perform measurement of the diameter of the femoral head on the AP Hip radiograph is as follows:

1. The AP Hip radiograph was uploaded to the Image J programme.

2. The technique in 3.31 was performed to display the circumference of the Femoral Head on the AP Hip radiograph.

3. The diameter of the circumference of the Femoral Head was measured using the ‘Scale Bar’ Tool. This is a function tool of the Image J system which automatically measures the on-screen diameter of a circle that has been created by the ‘Circle Fitting’ Tool. (see Figure 4.14). This was performed three times.

4. The mean of the three measures was calculated to provide a mean diameter.

Figure 4.14: Use of the ‘Scale Bar’ Tool to measure the Diameter of the Femoral Head on the AP Radiograph.
4.34 Measurement of the Diameter of the Femoral Head on the Lateral Hip Radiograph

The technique to perform measurement of the diameter of the femoral head on the Lateral Hip radiograph is as follows:

1. The Lateral Hip radiograph was uploaded to the Image J programme.

2. The technique in 3.32 was performed to display the circumference of the Femoral Head on the Lateral Hip radiograph

3. The diameter of the circumference was measured using the ‘Scale Bar’ Tool with the length obtained from the results section (see Figure 4.15). This was performed three times.

![Figure 4.15: Use of the ‘Scale Bar’ Tool to measure the Diameter of the Femoral Head on the Lateral Radiograph.](image)

4. The mean of the three measures was calculated to provide a mean diameter.
4.35 Measurement of the Diaphyseal and Cortical Widths of the Proximal Femur on the AP Hip Radiograph

The technique to perform measurement of the diaphyseal and cortical widths of the proximal femur on the AP Hip radiograph is as follows:

1. The AP Hip radiograph was uploaded to the Image J programme.

2. A measurement of one femoral head diameter directly inferior to the superior most aspect of the lesser trochanter was made using the distance measuring tool with the level marked on the radiographs (see Figure 4.16).

![Figure 4.16: The AP Hip Radiograph marked to show the area one femoral head diameter inferior to the superior most aspect of the lesser trochanter.](image)

The use of the femoral head diameter allowed for uniformity in dimensions among patients.
3. The contrast and brightness enhancing tools were utilised to define the full width of the proximal femoral diaphysis at this level.

4. The Diaphyseal Width was measured at this region (see Figure 4.17)

![Figure 4.17: The Width of Femoral Diaphysis One Femoral Head Diameter beneath the Lesser Trochanter.](image)

5. The measurement was made three times with a mean obtained.

6. The width of the Lateral Femoral Cortex was measured (see Figure 4.18).

![Figure 4.18: The Width of the Lateral Femoral Cortex One Femoral Head Diameter beneath the Lesser Trochanter.](image)

7. The measurement was made three times with a mean obtained.

8. The width of the Medial Femoral Cortex was measured (see Figure 4.19).
9. The measurement was made three times with a mean obtained.

10. A measurement of one half of the femoral head diameter inferior to this region was made using the distance measuring tool with the level marked on the radiographs.

11. The contrast and brightness enhancing tools were utilised to define the full width of the diaphysis at this level.
12. The Diaphyseal Width was measured at this region (see Figure 4.20).

Figure 4.20: The Width of Femoral Diaphysis One and a Half Femoral Head Diameters beneath the Lesser Trochanter.

13. The measurement was made three times with a mean obtained.

14. The width of the Lateral Femoral Cortex was measured (see Figure 4.21).

Figure 4.21: The Width of the Lateral Femoral Cortex One and a Half Femoral Head Diameters beneath the Lesser Trochanter.
15. The measurement was made three times with a mean obtained.

16. The width of the Medial Femoral Cortex was measured (see Figure 4.22).

![Figure 4.22: The Width of the Medial Femoral Cortex One and a Half Femoral Head Diameter beneath the Lesser Trochanter.](image)

17. The measurement was made three times with a mean obtained.
4.36 Measurement of the Diaphyseal and Cortical Widths of the 5th Metacarpal on the PA Wrist Radiograph

The technique to perform measurement of the diaphyseal and cortical widths of the 5th Metacarpal on the PA radiograph is as follows:

1. The PA radiograph of the Wrist was uploaded to the Image J programme (see Figure 4.23).

2. The image was magnified to 400%

3. The 5th Metacarpal was centred on the screen (see Figure 4.24)
4. The length of the 5\textsuperscript{th} Metacarpal was measured along its anatomical axis (see Figure 4.25). This was performed by placing a point in the middle of the distal joint surface of the metacarpal and a point in the middle of the proximal joint surface of the metacarpal, with a line drawn between the two points.

![Figure 4.25: The Anatomical Axis of the 5\textsuperscript{th} Metacarpal on the PA Wrist Radiograph.](image)

5. The midpoint of this axis was marked as the midpoint of the 5\textsuperscript{th} metacarpal.

6. The contrast and brightness enhancing tools were utilised to define the full width of the diaphysis of the 5\textsuperscript{th} metacarpal at this level.

7. The Diaphyseal Width was measured at this region (see Figure 4.26).

![Figure 4.26: The Width of the Mid Diaphysis of the 5\textsuperscript{th} Metacarpal on the AP Wrist Radiograph.](image)
8. The measurement was made three times with a mean obtained.

9. The width of the Radial Cortex was measured at this region (see Figure 4.27).

![Figure 4.27: The Width of the Radial Cortex of the Mid Diaphysis of the 5th Metacarpal.](image)

10. The measurement was made three times with a mean obtained.

11. The width of the Ulnar Cortex was measured at this region (see Figure 4.28).

![Figure 4.28: The Width of the Ulnar Cortex of the Mid Diaphysis of the 5th Metacarpal.](image)

12. The measurement was made three times with a mean obtained.
4.37 Measurement of the Diaphyseal Widths of the 5\textsuperscript{th} Metacarpal on the Lateral Wrist Radiograph

The technique to perform measurement of the diaphyseal and cortical widths of the 5\textsuperscript{th} Metacarpal on the Lateral radiograph is as follows:

1. The Lateral radiograph of the Wrist was uploaded to the Image J Programme (see Figure 4.29).

![Figure 4.29: The Lateral Wrist Radiograph](image)

2. The image was magnified to 400%

3. The 5\textsuperscript{th} Metacarpal was centred on the screen (see Figure 4.30)

![Figure 4.30: The Lateral Wrist Radiograph Magnified and Centred on the 5\textsuperscript{th} Metacarpal.](image)
4. The full length of the 5th Metacarpal was measured along its anatomical axis (see Figure 4.31). This was performed by placing a point in the middle of the distal joint surface of the metacarpal and a point in the middle of the proximal joint surface of the metacarpal, with a line drawn between the two points.

![4.31: The Anatomical Axis of the 5th Metacarpal on the Lateral Wrist Radiograph.](image)

5. The midpoint of this axis was marked as the midpoint of the 5th metacarpal.

6. The contrast and brightness enhancing tools were utilised to define the full width of the diaphysis of the 5th metacarpal at this level.

7. The Diaphyseal Width was measured at this region (see Figure 4.32).

![Figure 4.32: The Width of the Mid Diaphysis of the 5th Metacarpal on the Lateral Wrist Radiograph.](image)
8. The measurement was made three times with a mean obtained.

4.38 Measurement of the Diaphyseal and Cortical Widths of the 2\textsuperscript{nd} Metacarpal on the PA Wrist Radiograph

The technique to perform measurement of the diaphyseal and cortical widths of the 2\textsuperscript{nd} Metacarpal on the PA radiograph was as follows:

1. The PA radiograph of the Wrist was uploaded to the Image J programme.

2. The technique as described in 3.36 for the 5\textsuperscript{th} metacarpal was applied to the 2\textsuperscript{nd} metacarpal.

4.39 Measurement of the Diaphyseal and Cortical Widths of the Radial Diaphysis on the PA Wrist Radiograph

The technique to perform measurement of the diaphyseal and cortical widths of the Radial Diaphysis on the PA radiograph was as follows:

1. The PA radiograph of the Wrist was uploaded to the Image J programme.

2. The image was magnified to 400%.

3. The Distal Radius was centred on the screen (see Figure 4.33).

4. The brightness and contrast tools were enhanced to achieve full visualisation of the distal radial and ulna.

Figure 4.33: The PA Wrist Radiograph Magnified and Centred on the Distal Radius.
5. The width of the distal radial articular surface was measured, from the most distal radial aspect of the radial styloid to the most ulnar aspect of the distal radial articular surface, using the measuring tool (see Figure 4.34).

![Figure 4.34: The Width of the Distal Articular Surface on the PA Wrist Radiograph.](image)

6. This was repeated 3 times and a mean value was calculated.

7. The midpoint of the line measuring the width of the distal radial articular surface was identified.

8. A line measuring two widths of the distal radial articular surface was drawn proximally from the midpoint of the distal radial articular surface (see Figure 4.35).

![Figure 4.35: The Radial Diaphysis Two ‘Distal Radial Articular Surface’ Widths from the Distal Radial Articular Surface.](image)

8. The contrast and brightness enhancing tools were utilised to define the full width of the radial diaphysis at this level.
9. The width of the radial diaphysis was measured at this region (see Figure 4.36).

10. The measurement was made three times with a mean obtained.

11. The width of the radial cortex of the radial diaphysis was measured (Figure 4.37).

12. The measurement was made three times with a mean obtained.
13. The width of the ulnar cortex of the radial diaphysis was measured (see Figure 4.38).

![Figure 4.38: The Width of the Ulnar Cortex of the Radial Diaphysis on the PA Wrist Radiograph.](image)

14. The measurement was made three times with a mean obtained.

4.40 Measurement of the Diaphyseal and Cortical Widths of the Ulnar Diaphysis on the PA Wrist Radiograph

The technique to perform measurement of the diaphyseal and cortical widths of the ulna on the PA radiograph was as follows:

1. The PA radiograph of the Wrist was uploaded to the Image J programme.

2. The technique as described in 4.39 was used to identify a point on the radial diaphysis two widths of the distal radial articular surface proximally from the midpoint of the distal radial articular surface (see Figure 4.35).

3. The corresponding point at the same level on the ulnar diaphysis was identified.
4. The contrast and brightness enhancing tools were utilised to define the full width of the ulnar diaphysis at this level.

5. The width of the ulnar diaphysis was measured at this region (see Figure 4.39).

![Figure 4.39: The Width of the Ulnar Diaphysis on the PA Wrist Radiograph.](image)

6. The measurement was made three times with a mean obtained.

7. The width of the radial cortex of the ulnar diaphysis was measured (see Figure 4.40).

![Figure 4.40: The Width of the Radial Cortex of the Ulnar Diaphysis on the PA Wrist Radiograph.](image)

8. The measurement was made three times with a mean obtained.
9. The width of the Ulnar Cortex of the Ulnar Diaphysis was measured (see Figure 4.41).

Figure 4.41: The Width of the Ulnar Cortex of the Radial Diaphysis on the PA Wrist Radiograph.

10. The measurement was made three times with a mean obtained.
4.4 The Manufacture of the Aluminium Step Wedge

This section describes the manufacture of the aluminium step wedge used in the study.

The design of the aluminium step wedge was validated by Dawson (2009).
It was manufactured by the University of Edinburgh Engineering Workshop, Kings Building under the direction of Mr Andrew Downie.

The material chosen for manufacture was Duralumin, an aluminium alloy containing aluminium, copper, magnesium and manganese.

The dimensions of the device were height 75mm by length 75mm by thickness 30mm (see Figure 4.42). It had 15 steps on its surface each 5mm in height.

![Figure 4.42: The Aluminium Step Wedge](image)

For the quality assurance system of production, the tolerance level was set at +/-0.2mm. The object was debarred to avoid sharp edges. It was suitable for autoclave sterilisation.

4.5 The Use of the Aluminium Step Wedge and Ball Bearing in the Digital Radiographs

4.51 The Use of the Aluminium Step Wedge in the Digital Radiographs

This section describes the use of the Aluminium Step Wedge in the study.
In order to establish aluminium equivalent values of bone, an aluminium step wedge had to be incorporated into the Radiographs. When this had been piloted in laboratory studies, it was established that the step wedge had to be positioned as close to the Region of Interest (ROI) as possible to allow an accurate calibration and aluminium equivalent analysis. It also had to be included in the Radiographs in a manner that it was fully visible, with its upper surface perpendicular to the X-ray beam. Lastly it had to be at a similar depth to the fracture site, to normalise for attenuation of the X-ray beams with distance travelled (Dawson, 2009). However it had to be positioned such that it did not interfere with imaging of the fracture site.

The positioning of the step wedge within the hip radiographs proved challenging:

1. Attempts at positioning the step wedge as close to the ROI were limited by the considerable thickness of soft tissue surrounding the proximal femur (see Figure 4.43). As such the step wedge was positioned as close to the ROI as the soft tissue would allow.

![Figure 4.43: Use of the Aluminium Step Wedge in the Hip Radiographs – demonstration of the soft tissue preventing positioning of the Step Wedge at the ROI.](image)

2. It was not possible to include the step wedge in the AP Pelvis radiograph due to the volume occupied by the patient in the field of the radiograph (see Figure 4.44). As such the aluminium step wedge could only be included in the AP Hip Radiograph. This prevented the assessment of the aluminium equivalent values of the uninjured hip.
3. It was not possible to achieving upright positioning of the step wedge, when placed on the bed, beside the patient. When attempting this, the step wedge would follow the contour of the mattress, sloping down towards the patient, such that the upper surface was not perpendicular to the X-ray beam (see Figure 4.45).

To correct this, a Perspex jig (see Figures 4.46) was created, which attached onto the trolley allowing for the step wedge to be positioned beside the fracture site in an upright position (see Chapter 4.7). This jig had an extendable suspension platform, allowing the step wedge to be positioned as close to the ROI as possible.
Placement of the Step Wedge in the wrist radiographs was far less challenging as the step wedge could lie on the X-ray plate beside the fracture site in an upright position (see Figures 4.47).

Figure 4.46: The Orientation of the Aluminium Step Wedge with the Perspex jig: a) the Caudal View; b) the Side View; c) the Radiograph View.

Figure 4.47: Use of the Aluminium Step Wedge in the Wrist Radiographs: a) the Proximal View; b) the Radiograph View.
4.52 The Use of the Ball Bearing in the Digital Radiographs

This section describes the use of the Ball Bearing in the digital radiographs.

The technique of establishing aluminium equivalent measures of the hip and wrist from the digital radiographs, as described by Dawson (2009), required measurement of and correction for the depth of the soft tissue and bone through which the x-ray beams travel. These measures were calculated from the lateral radiographs. To allow this, known dimensions were required on the AP/PA and lateral radiographs.

Inclusion of the step wedge in the AP/PA radiograph provided a known dimension in this image. To provide a known dimension in the lateral radiograph, a stainless steel ball bearing of diameter 20 mm was included (see Figure 4.48).

![Figure 4.48: The Ball Bearing: a) the Front View; b) the Side View.](image)

For the hip radiograph, this taped to the anterior aspect of the thigh, one hand length beneath the greater trochanter of the injured hip (see Figure 4.49).
In the wrist radiograph, this was placed adjacent to the injured forearm, one hand breadth beneath the radio-carpal joint of the affected wrist (see Figure 4.50).

Use of these fixed measures to calculate soft tissue and bone dimensions are detailed in Chapter 4.8.
4.6 The Manufacturing and Use of the Perspex Jig

The jig was created to allow the aluminium step wedge to sit upright, beside the patient, perpendicular to the X-ray beams, enabling the step wedge to be analysed accurately in the MatLab Programme (see Figure 4.51). This jig was created in conjunction with the Medical Physics Department Workshop at the Royal Infirmary of Edinburgh.

Figure 4.51: The Perspex Jig: a) the Side View; b) the Anterior View; c) the Posterior View; d) the Base View.

This jig attached onto the railings of the patient trolley by the aid of a metallic hook (see Figure 4.52). At the bottom of the jig, at the level of the mattress, there was a Perspex floor, which was adjustable and could be extended towards the patient (see Figure 4.52c).
This provided a solid, flat platform on which to place the aluminium step wedge and extend it as close to the patient as possible. However, use of this jig meant that the calibration measurements taken from the aluminium step wedge were offset by the gray level attenuation performed by the Perspex in the jig. Such an attenuation process would not be experienced by the proximal femur as there was no such Perspex beneath it. As such it was necessary to perform calibration equations in order to allow for the effects of this attenuation process to be accounted for, in the calculation of aluminium equivalent measures. This process is described in Chapter 4.12.

4.7 The Use of the Aluminium Step Wedge and Ball Bearing to Define ‘Real Time’ Dimensions in the Digital Radiographs

This section describes the use of the ‘known’ dimensions’ of the aluminium step wedge and the ball bearing to define the ‘real time’ dimensions in the digital radiographs.
4.71 The Use of the Aluminium Step Wedge to Define ‘Real Time’ Dimensions in the AP Hip and PA Wrist Digital Radiographs

The known dimensions of the Aluminium Step Wedge could be used to calculate the real time dimensions of the bone and soft tissue measures in the AP Hip and PA Wrist radiographs from the following equation (see Figure 4.53):

\[ Y \text{ (mm)} = \frac{30 \times Z}{X} \]

Where:

- \( Y \) = Bone or Soft Tissue Measure in real time (mm)
- \( Z \) = Bone or Soft Tissue Measure in radiograph (mm)
- \( X \) = Step Wedge Breadth in radiographs (mm)
- 30 (mm) = Step Wedge Breadth in real time

![Figure 4.53: Dimension Analyses in the Radiographs: a) the AP Hip Radiograph; b) the PA Wrist Radiograph.](image)

The bottom step of the step wedge was used for calibration purposes and the contrast and brightness tool were utilised to define the full width of this step accordingly.
The Use of the Ball Bearing to Define ‘Real Time’ Dimensions in the Lateral Hip and Wrist Digital Radiographs

The fixed dimensions of the Ball Bearing could be used to calculate the real time dimensions of the soft tissue and bone thickness in the lateral Hip and Wrist radiographs from the following equation (see Figure 4.54):

\[ Y (\text{mm}) = \frac{(20 \times Z)}{X} \]

Where:
- \( Y \) = Bone or Soft Tissue Measure in real time (mm)
- \( Z \) = Bone or Soft Tissue Measure in radiograph (mm)
- \( X \) = Ball Bearing Diameter in radiographs (mm)
- 20 (mm) = Ball Bearing Diameter in real time

Figure 4.54: Dimension Analyses in the Radiographs: a) the Lateral Hip Radiograph; b) the Lateral Wrist Radiograph.

The use of such equations in depended on the inclusion of objects with known dimensions (i.e. the step wedge and the ball bearing) in the AP/PA and lateral radiographs. While inclusion of the step wedge in the AP/PA radiograph was
relatively simple to achieve, inclusion of a ball bearing in the lateral radiograph would be more difficult to achieve in routine clinical practice. Therefore, a technique was required to allow calculation of dimensions on the lateral radiograph from known dimensions on the AP/PA radiograph. For the hip radiographs, the concept of the femoral head being spherical was utilised. For the wrist radiographs, the concept of the midpoint of the fifth metacarpal diaphysis being cylindrical was utilised. Both techniques are validated below.

4.8 The Use of the Femoral Head as a Sphere to correlate dimension measures in the AP and Lateral Hip Radiographs

This section describes the technique used to establish the Femoral Head as a sphere and use this to correlate dimension measures between the AP and Lateral Hip Radiographs.

The technique for this was as follows:

1. The AP Hip Radiograph was uploaded to Image J Programme.

2. The technique as described in Chap 4.31 was used to delineate the circumference of the femoral head on the AP Hip Radiograph (see Figure 4.53a).

3. The technique as described in Chap 4.33 was used to delineate and measure the diameter of the femoral head on the AP Hip Radiograph (see Figure 4.53a).

4. This procedure was performed three times and a mean obtained for the diameter of the femoral head on the AP Hip Radiographs.

5. From the same AP Hip radiograph, the width of the base of the Step Wedge was measured three times using the measuring tool, at 400% magnification. The real time dimension of this was known to be 30mm (see Figure 4.53a).
6. Using the equations in Chapter 4.71, the real time Femoral Head Diameter in the AP Hip Radiograph was calculated.

7. The Lateral Hip Radiograph was uploaded to Image J Programme.

8. The technique as described in Chapter 4.32 was used to delineate the circumference of the femoral head on the Lateral Hip Radiograph (see Figure 4.54a).

9. The technique as described in Chapter 4.34 was used to delineate and measure the diameter of the femoral head on the Lateral Hip Radiograph (see Figure 4.54a).

10. This procedure was performed three times and a mean obtained for the diameter of the femoral head on the Lateral Hip Radiographs.

11. From the same Lateral Hip radiograph, the diameter of the Ball Bearing was measured three times using the measuring tool, at 400% magnification. The real time dimension of this was known to be 20mm.

12. Using the equations in Chapter 4.72, the real time Femoral Head Diameter in the Lateral Hip Radiograph was calculated (see Figure 4.54a).

It was possible to perform the full procedure on the AP and Lateral hip radiographs of 27 of the patients.

The Pearson R Correlation between the femoral head diameters of the AP and Lateral Radiographs was 0.925 p<0.001 (see Figure 4.55).
The statistically significant correlation between the femoral head diameters on the AP and lateral hip radiographs, supported the use of this technique in clinical practice.

4.9 Use of the Fifth Metacarpal Mid-Diaphysis as a Cylinder to correlate dimension measures between the PA and Lateral Wrist Radiographs

This section describes the technique used to establish the Fifth Metacarpal Mid-Diaphysis as a cylinder and use this to correlate dimensions measured between the PA and Lateral Wrist Radiographs.

The technique for this is as follows:

1. The PA Wrist Radiograph was uploaded to Image J Programme.
2. The technique as described in Chap 4.36 was used to delineate the mid-point of the fifth metacarpal diaphysis on the PA Wrist Radiograph (see Figure 4.53b).
3. The technique as described in Chapter 4.36 was used to measure the width of the midpoint of fifth metacarpal diaphysis on the PA Wrist Radiograph (see Figure 4.53b).

4. This procedure was performed three times and a mean obtained for the cortical width of the midpoint of fifth metacarpal diaphysis on the PA Wrist Radiograph.

5. From the same PA Wrist radiograph, the width of the base of the Step Wedge was measured three times using the measuring tool, at 400% magnification. The real time dimension of this was known to be 30mm.

6. Using the equations in Chapter 4.71, the real time width of the midpoint of fifth metacarpal diaphysis on the PA Wrist Radiograph was calculated (see Figure 4.53b).

7. The Lateral Wrist Radiograph was uploaded to Image J Programme.

8. The technique as described in Chapter 4.37 was used to delineate the midpoint of the fifth metacarpal diaphysis on the Lateral Wrist Radiograph (see Figure 4.54b).

9. The technique as described in Chapter 4.37 was used to measure the width of the midpoint of fifth metacarpal diaphysis on the Lateral Wrist Radiograph (see Figure 4.54b).

10. This procedure was performed three times and a mean obtained for the width of the midpoint of fifth metacarpal diaphysis on the Lateral Wrist Radiograph.

11. From the same Lateral Wrist radiograph, the diameter of the Ball Bearing was measured three times using the measuring tool, at 400% magnification. The real time dimension of this was known to be 20mm (see Figure 4.54b).

12. Using the equations in Chap 4.72, the real time cortical width of the midpoint of fifth metacarpal diaphysis on the Lateral Wrist Radiograph was calculated.
It was possible to perform the full procedure on the AP and Lateral hip radiographs of 49 of the patients.

The Pearson R Correlation between the femoral head diameters of the AP and Lateral Radiographs was 0.918 p<0.001 (see Figure 4.78).

Figure 4.56: The Correlation Analysis between the Fifth Metacarpal Mid-Diaphyseal Width on the PA and Lateral Radiographs.

The statistically significant correlation between the mid diaphyseal widths of the 5th metacarpal on the PA and Lateral Wrist radiographs, supported the use of this technique in clinical practice.
4.10 Use of Contrast Enhancing Tool on Image J and PACS to Define the Singh Index

This section describes the use of the contrast enhancing and magnification tools on both Image J and PACS to Define the Singh Index on the Hip Radiographs.

The Singh Index is a six point scale as described by Singh et al. (1970), which grades the quality of bone at the hip based on the presence, quantity and location of the compressive and tensile bone trabeculae in the proximal femur (see Figure 2.1).

In this section of the study, initial assessment of the radiographs comprised assignment of a Singh Index Grade (as directed by Singh et al., 1970) to each ‘original’ radiograph by the principal study investigator both on the PACS system (PACS Radiographs) and the Image J system (FUJI Radiographs). Assessment was performed on the contralateral hip on the AP Pelvic Radiograph as the fracture prevented adequate assessment of the trabecular pattern of the injured hip.

Magnification of the radiographs was performed throughout to assist in detection of the trabeculae (see Figures 4.57a and 4.58a).

On both systems, images were then fully inverted to assess for further trabeculae that were not visible on the ‘original’ radiographs. If previously unseen trabeculae were noted, these were documented, and a new grading given as appropriate for these ‘inverted’ radiographs (see Figures 4.57b and 4.58b).

The radiographs were then re-inverted and contrast fully reduced to produce a black image. The contrast was then lightened in a graduated fashion, with assessment of trabeculae performed throughout. Again, if previously unseen trabeculae were noted, these were documented, and a new grading given as appropriate for these ‘contrast-enhanced’ radiographs (see Figures 4.57c and 4.58c).
4.11 Use of the MatLab Programme for Radiograph Analysis

This section describes the technique used to analyse the Digital Radiographs on the MatLab Programme to establish Aluminium Equivalent Measures of the Proximal Femur and Distal Radius. This technique was validated by Dawson (2009):

1. Upload the Digital Radiograph to the MatLab Programme.
2. Measure the grey level of the ROI, i.e. over the bone and the steps of the wedge.
3. Convert all grey levels to dose.
4. Subtract 15% dose from the ROI to account for no scatter equipment being present.
5. Calculate the percentage dose added for each step of the wedge due to the absence
of the scatter equipment and subtract this.
6. Correct each step of the wedge for scatter by finding the percentage scatter dose from the double exponential scatter graph and subtract this.
7. Correct the ROI for scatter by finding the percentage scatter dose for the overlying Soft Tissue from the straight line graph (Dawson, 2009).
8. Find the dose attenuated by the overlying Soft Tissue using the exponential graph (Dawson, 2009) and add this to the ROI scatter-free dose.
9. Convert the final ROI dose and scatter-free steps doses to grey values.
10. Fit the exponential calibration graph to the step values (Dawson, 2009).
11. Calculate the Aluminium-equivalent thickness of the ROI using the calibration graph.
12. Divide Aluminium-equivalent by thickness of bone (mm) from lateral radiograph.

4.12 Modification of the MatLab Equations for the Perspex Jig used in the Hip Radiographs

This section describes the technique used to account for the X-ray attenuation imparted by inclusion of the Perspex jig within the AP hip radiograph. This attenuation is incorporated into the analysis of the aluminium equivalent measures to provide a ‘Perspex’ corrected figure for aluminium equivalent density.

The above equations in Chapter 3.11 were created using a set-up where the aluminium step wedge and the bone specimen were both placed on the X-ray plate. This was the set-up used for the wrist radiographs and so these equations could be used directly. The situation of the hip radiographs was however complicated by the fact that both the patient and the aluminium step wedge were placed on a trolley and a mattress above the X-ray plate, as well as the fact that the aluminium step wedge was placed on the Perspex jig as described above. These attenuated the X-ray beams travelling to the X-ray plate and so had to be considered when formulating results.
On consideration of the effects of the mattress and the trolley, it was considered that since these would equally affect both the patient and the step wedge, corrections for these could be avoided. However, with the aluminium step wedge sitting additionally on the Perspex jig, this was accounted for when calculating aluminium equivalent measures of BMD.

The degree of X-ray attenuation imparted by the Perspex jig was investigated by taking a set of three radiographs with the aluminium step wedge sitting on the mattress and then another set of three radiographs with aluminium step wedge sitting on the Perspex jig above the mattress (see Figure 4.59). A phantom limb was included in the analysis to provide a representative situation of the clinical X-ray process. The difference in the mean recorded aluminium equivalent measures from the each step of the step wedge in the two sets of radiographs was assessed and an equation created to correct for the effect of the Perspex jig. The results of these are detailed in Appendix 3.

Figure 4.59: The Effects of the Perspex Jig on the Aluminium Equivalent Values: a) the Step Wedge on the mattress alone; b) the Step Wedge on the Perspex Jig and the mattress.
From assessment of the difference between the two results, it was found that the difference could be accounted for by either the exponential equation:

\[ f(x) = a^\exp(b^x) \]

Coefficients (with 95% confidence bounds):

\[
a = 133.9 \ (127.3, \ 140.4) \\
b = 0.002523 \ (0.002431, \ 0.002614) 
\]

or the polynomial equation:

\[ f(x) = p1^x + p2 \]

Coefficients (with 95% confidence bounds):

\[
p1 = 1.171 \ (1.12, \ 1.223) \\
p2 = -106.2 \ (-133, \ -79.37) 
\]

The goodness of fit data for the exponential equation was:

SSE: 89.16; R-square: 0.9984; Adjusted R-square: 0.9981; RMSE: 3.338.

While the goodness of fit data for the polynomial equation was:

SSE: 156.5; R-square: 0.9971; Adjusted R-square: 0.9968; RMSE: 4.422.

The general exponential equation was chosen due to its improved accuracy. The technique used to establish Aluminium Equivalent Measures of BMD of the Proximal Femur was modified thus to account for inclusion of the Perspex jig:
1. Upload the Digital Radiograph to the MatLab Programme.
2. Measure the grey level of the ROI, i.e. over the bone and the steps of the wedge.
3. Convert all grey levels to dose.
4. Convert Step Wedge Grey Levels to Perspex Corrected Step Wedge Grey Levels using the equation $y = ae^{(bx)}$:
   where $y$ is corrected Grey Level, $x$ is non-corrected Grey Level, $a=133.9$, $b=0.002523$
5. Subtract 15% dose from the ROI to account for no scatter equipment being present.
6. Calculate the percentage dose added for each step of the wedge due to the absence of the scatter equipment and subtract this.
7. Correct each step of the wedge for scatter by finding the percentage scatter dose from the double exponential scatter graph and subtract this.
8. Correct the ROI for scatter by finding the percentage scatter dose for the overlying Soft Tissue from the straight line graph (Dawson, 2009).
9. Find the dose attenuated by the overlying Soft Tissue using the exponential graph (Dawson, 2009) and add this to the ROI scatter-free dose.
10. Convert the final ROI dose and scatter-free steps doses to grey values.
11. Fit the exponential calibration graph to the step values (Dawson, 2009).
12. Calculate the Aluminium-equivalent thickness of the ROI using the calibration graph.
13. Divide Aluminium-equivalent by thickness of bone (mm) from lateral radiograph.
4.13 Statistics

This section describes the Statistical Analyses employed within this study.

The correlations between DXA BMD values versus the Cortical Measures, the Trabecular Patterns and the Aluminium Equivalent Measures were performed with Pearson R Correlation Models (for normally distributed data) and Spearman Rank Correlation Models (for non-normally distributed data and datasets with significant outliers). Normality of datasets was assessed for with the Shapiro-Wilks W test. Comparison of Correlation Co-efficient Values was performed with the Fisher r-to-z transformation (z) statistical test.

With the cohorts available for analysis (around 30 patients), both the Pearson Correlation Model and the Spearman Rank Correlation Model was able to detect a moderate correlation (minimum significant correlation coefficient (r) value of 0.56) with a power of 0.95 and an alpha value of 0.05.

As the data was predominantly interval in nature, Pearson R Correlation values were chosen for the final comparative results in the study.

The Pearson’s r co-efficient was also used to assess intra-observer reliability of the Singh Index Assessment Techniques.

The Student T test was used to perform univariate statistical comparisons between two continuous variables. The One-Way Analysis of Variance (ANOVA) Test was used to perform statistical comparisons between three or more continuous variables, with post-hoc Bonferroni Tests performed to assess for individual differences between variables.

For all statistical tests, the significance level was set at p<0.05.
Part V

DXA
5.1 DXA as the Gold Standard Measure for Bone Mineral Density

This section describes the use of DXA as a gold standard measure for BMD against which to compare the BMD estimates measured in this thesis.

At present there are two major methods of BMD estimation – DXA and QCT (Ramachandran, 2006). The benefits and limitations of both are discussed in the literature review. Essentially, DXA provides a measure of bone mineral ‘area density’ through an absorptiometry technique, while QCT provides a true measure of BMD (Stromsoe, 2004). Both techniques provide similar results, particularly within the metaphyseal regions of the hip and the wrist (Stromsoe, 2004). There are however a number of other factors which determine uptake of use, namely availability, cost and radiation exposure (SIGN, 2003).

As DXA was the gold standard method for BMD estimation within NHS Lothian, this was chosen as the gold standard measure for BMD for this study.

The process of referral for DXA Scanning within NHS Lothian is detailed in Chapters 2 and 3 (SIGN, 2003). In summary, all patients who have been diagnosed with fragility fractures (hip, wrist, lumbar spine) in NHS Lothian were referred for DXA Scanning by their treating centre three to six months post-fracture (SIGN, 2003). This was performed by sending a copy of the patient’s discharge summary or first orthopaedic clinic visit to the DXA service at the Western General Hospital, Edinburgh.

In NHS Lothian, the DXA scan routinely measures BMD at the patient’s hip and lumbar spine (see Figure 5.1).
Figure 5.1: NHS Lothian Standard DXA Reports: a) Hip DXA Report; b) Lumbar Spine DXA Report.

Following hip fractures, the BMD of the contralateral hip is analysed.

For very specific purposes, the BMD of the forearm can be assessed with DXA (see Figure 5.2). However this is not routine practice. As such favourable ethical opinion was sought and obtained to allow a cohort of wrist fracture patients to have a DXA scan analysis of their contralateral forearm when they attended their routine DXA scan. The process of care for this part of the study is described in Chapter 3.2. This provided comparison data against which to compare the radiographic measures and aluminium equivalent values.
The DXA results were stored in the computer archives of the DXA department, Western General Hospital, Edinburgh. These were accessed under guidance of the DXA Team, with the results downloaded in an anonymous, coded form. This allowed identification of results at a later date to compare against the radiographic measures and aluminium equivalent values.
5.2 Use of DXA as a Comparison Measure for the Hip Radiographs

The hip DXA analysis provided BMD readings from the intertrochanteric region, the femoral neck region and the trochanteric region as well as the whole hip region.

When performing the analyses, the BMD measures made in this thesis were compared against all four hip DXA values. It was hypothesised that the intertrochanteric reading would provide the strongest correlation with the results as this was closest to the ROI (see Figure 5.3; ROI is the blue square.)

Figure 5.3: BMD in the Hip Radiographs: the ROI is marked with the Blue Square.

The radiographic measures and aluminium equivalent values were taken from the injured hip whilst the DXA results were taken from the contralateral hip.

It was considered that this was justified based on the findings from Hwang et al. (2012). This retrospective cohort study assessed bilateral hip DXA results from 384 post-menopausal females, with the bilateral DXA Scans performed during the same session. They found that the mean (SD) Total Hip BMD was 0.693 (0.16) on the
right side and 0.697 (0.17) on the left side. They also found that the mean BMD of the Intertrochanteric Region of the Hip was 0.838 (0.17) on the right side and 0.843 (0.17) on the left side. There was no statically significant difference between both sets of values and the maximum error difference between them was 6% (Hwang et al., 2012). Given this concordance between the bilateral Hip DXA values, the use of the contralateral Hip DXA values was considered acceptable in this study.
5.3 Use of DXA as a Comparison Measure for the Wrist Radiographs

The forearm DXA analysis provided BMD readings from the ultra-distal region (distal juxta-articular region of radius and ulna), the mid-distal region (metaphyseal region of radius and ulna) and the proximal third region (distal diaphyseal region of radius and ulna), as well as the whole forearm region.

When performing the analyses, the BMD readings measured in this study were compared against all four forearm values. The results were also against the whole hip values as previous studies had shown there was moderate correlations between these regions (Cummings et al., 1993). It was hypothesised that the ultra-distal value would provide the strongest correlation with the measures in this thesis as this was closest to the ROI (see Figure 5.4; ROI is the blue square.)

Figure 5.4: BMD in the Wrist Radiographs: the ROI is marked with the Blue Square.
The radiographic measures and aluminium equivalent values were taken from the injured wrist whilst the DXA results were taken from the contralateral forearm.

It was considered that this was justified based on the findings of Sergi et al. (2009) and Taaffe et al. (1994). They assessed variations in bilateral forearm DXA readings from cohorts of 60 healthy adults respectively: 30 men and 30 female (Sergi et al., 2009); 35 elderly females (mean age 68 years) and 25 young females (mean age 27 years)(Taaffe et al., 1994). Sergi et al. (2009) found no significant difference between the forearm DXA values of the dominant and non-dominant forearms, while Taafe et al. (1994) reported percentage differences between dominant and non-dominant forearm DXA values of 1.8% for the young cohort and 1.0% for the elderly cohort. Given this concordance between bilateral forearm DXA values, the use of the contralateral forearm DXA values was considered acceptable.
RESULTS

Part VI

Use of Cortical Measures in the Digital Radiographs to Assess Bone Mineral Density
Use of Cortical Measures in the Digital Radiographs to Assess Bone Mineral Density

6.1 The Image J Analysis Programme

The analysis process for the measurement of cortical dimensions from the digital radiographs of the hip and wrist using the Image J programme has been described in Chapter 4.

6.2 Cortical Measures in the Hip Radiographs

This section provides the results of the analyses of the cortical measures from the AP Hip Radiographs and correlates them with the DXA measures.

The cortical measures taken for the AP hip radiographs included the width of the lateral femoral cortex one femoral head diameter beneath the lesser trochanter, the width of the medial femoral cortex one femoral head diameter beneath the lesser trochanter, the width of the lateral femoral cortex one and a half femoral head diameters beneath the lesser trochanter and the width of the medial femoral cortex one and a half femoral head diameters beneath the lesser trochanter.

The width of the femoral diaphysis one femoral head diameter beneath the lesser trochanter and the width of the femoral diaphysis one and a half femoral head diameters beneath the lesser trochanter were also measured to allow the calculation of respective Cortical Indices. Lastly, the four cortical measures were summed to given a combined cortical score similar to the Tingart Score (Tingart et al., 2003). These are described in the sections below.

It was hypothesised that external rotation of the proximal femur, secondary to the fracture, may influence the cortical measures recorded. This is addressed in Chapter 6.3.
6.21 The Width of the Lateral Femoral Cortex One Femoral Head Diameter beneath the Lesser Trochanter in the AP Hip Radiograph

This section describes the results obtained for the width of the lateral femoral cortex one femoral head diameter beneath the lesser trochanter in the AP Hip Radiograph and its correlations with DXA.

The process of performing this measurement is detailed in Chapter 4.35.

The Correlation Graphs between the DXA values of the Hip and this cortical measure are shown in Figure 6.1.

![Figure 6.1: Correlation between the Lateral Femoral Cortex 1 and: a) Intertrochanteric DXA; b) Femoral Neck DXA; c) Trochanteric DXA; d) Whole Hip DXA.](image)

The Pearson R Correlation values are provided in Table 6.1.

The DXA Values from the Intertrochanteric Region provided the strongest correlation with this cortical measure (see Figure 6.8).
6.22 The Width of the Medial Femoral Cortex One Femoral Head Diameter beneath the Lesser Trochanter in the AP Hip Radiograph

This section describes the results obtained for the width of the medial femoral cortex one femoral head diameter beneath the lesser trochanter in the AP Hip Radiograph and its correlations with DXA.

The process of performing this measurement is detailed in Chapter 4.35.

The Correlation Graphs between the DXA values of the Hip and this cortical measure are shown in Figures 6.2.

![Correlation Graphs](image)

The Pearson R Correlation values are provided in Table 6.1.

The DXA Values from the Intertrochanteric Region provided the strongest correlation with this cortical measure (see Figure 6.8).

![Figure 6.2](image)
6.23 The Cortical Index One Femoral Head Diameter beneath the Lesser Trochanter in the AP Hip Radiograph

This section describes the results obtained for the Cortical Index one femoral head diameter beneath the lesser trochanter in the AP Hip Radiograph and its correlations with DXA.

The process of performing this measurement is detailed in Chapter 4.35.

The Cortical Index one femoral head beneath lesser trochanter in the AP Hip Radiograph is calculated using the following formula:

\[
\text{Cortical Index} = \frac{(a+b)}{c}
\]

\[a = \text{Lateral Femoral Cortex one femoral head diameter beneath lesser trochanter}\]
\[b = \text{Medial Femoral Cortex one femoral head diameter beneath lesser trochanter}\]
\[c = \text{Femoral Diaphyseal Width one femoral head diameter beneath lesser trochanter}\]
The Correlation Graphs between the DXA values of the Hip and this Cortical Index are shown in Figure 6.3.

Figure 6.3: Correlation between the Cortical Index 1 and: a) Intertrochanteric DXA; b) Femoral Neck DXA; c) Trochanteric DXA; d) Whole Hip DXA.

The Pearson R Correlation values are provided in Table 6.1.

The DXA Values from the Intertrochanteric Region provided the strongest correlation with this cortical index (see Figure 6.8).
6.24 The Width of the Lateral Femoral Cortex One and a Half Femoral Head Diameters beneath the Lesser Trochanter in the AP Hip Radiograph

This section describes the results obtained for the width of the lateral femoral cortex one and a half femoral head diameters beneath the lesser trochanter in the AP Hip Radiograph and its correlations with DXA.

The process of performing this measurement is detailed in Chapter 4.35.

The Correlation Graphs between the DXA values of the Hip and this cortical measure are shown in Figure 6.4.

Figure 6.4: Correlation between the Lateral Femoral Cortex 2 and: a) Intertrochanteric DXA; b) Femoral Neck DXA; c) Trochanteric DXA; d) Whole Hip DXA.

The Pearson R Correlation values are provided in Table 6.1.

The DXA Values from the Trochanteric Region provided the strongest correlation with this cortical measure (see Figure 6.8).
6.25 The Width of the Medial Femoral Cortex One and a Half Femoral Head Diameters beneath the Lesser Trochanter in the AP Hip Radiograph

This section describes the results obtained for the width of the medial femoral cortex one and a half femoral head diameters beneath the lesser trochanter in the AP Hip Radiograph and its correlations with DXA.

The process of performing this measurement is detailed in Chapter 4.35.

The Correlation Graphs between the DXA values of the Hip and this cortical measure are shown in Figure 6.5.

![Correlation Graphs](image)

**Figure 6.5:** Correlation between the Medial Femoral Cortex 2 and: a) Intertrochanteric DXA; b) Femoral Neck DXA; c) Trochanteric DXA; d) Whole Hip DXA.

The Pearson R Correlation values are provided in Table 6.1.

The DXA Values from the Whole Hip Region provided the strongest correlation with this cortical measure (see Figure 6.8).
6.26 The Cortical Index One and a Half Femoral Head Diameters beneath the Lesser Trochanter in the AP Hip Radiograph

This section describes the results obtained for the Cortical Index one and a half femoral head diameters beneath the lesser trochanter in the AP Hip Radiograph and its correlations with DXA.

The process of performing this measurement is detailed in Chapters 4.35 and 6.23

The Correlation Graphs between the DXA values of the Hip and this Cortical Index are shown in Figure 6.6.

Figure 6.6: Correlation between the Cortical Index 1 and: a) Intertrochanteric DXA; b) Femoral Neck DXA; c) Trochanteric DXA; d) Whole Hip DXA.

The Pearson R Correlation values are provided in Table 6.1.

The DXA Values from the Intertrochanteric Region provided the strongest correlation with this Cortical Index (see Figure 6.8).
6.27 The Modified Tingart Score

This section describes the results obtained for Modified Tingart Score in the AP Hip Radiograph and its correlations with DXA.

The Modified Tingart Score was created using the following formula:

Modified Tingart Score = a+b+c+d

a= Lateral Femoral Cortex one femoral head diameter beneath lesser trochanter
b= Medial Femoral Cortex one femoral head diameter beneath lesser trochanter
c= Lateral Femoral Cortex one and a half femoral head diameters beneath lesser trochanter
d= Medial Femoral Cortex one and a half femoral head diameters beneath lesser trochanter
The Correlation Graphs between the DXA values of the Hip and this cortical score are shown in Figure 6.7.

![Figure 6.7: Correlation between the Modified Tingart Score and: a) Intertrochanteric DXA; b) Femoral Neck DXA; c) Trochanteric DXA; d) Whole Hip DXA.](image)

The Pearson R Correlation values are provided in Table 6.1. The DXA Values from the Intertrochanteric Region provided the strongest correlation with this cortical measure (see Figure 6.29).
Table 6.1: The Pearson R Correlation Values between the Proximal Femoral Cortical Measures and the Hip DXA Values

<table>
<thead>
<tr>
<th>Pearson Correlation</th>
<th>Intertrochanteric</th>
<th>Femoral Neck</th>
<th>Trochanteric</th>
<th>Whole Hip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral Femoral Cortex 1</td>
<td>.718 (p&lt;0.001)</td>
<td>.602 (p&lt;0.001)</td>
<td>.647 (p&lt;0.001)</td>
<td>.688 (p&lt;0.001)</td>
</tr>
<tr>
<td>Medial Femoral Cortex 1</td>
<td>.673 (p&lt;0.001)</td>
<td>.618 (p&lt;0.001)</td>
<td>.657 (p&lt;0.001)</td>
<td>.659 (p&lt;0.001)</td>
</tr>
<tr>
<td>Cortical Index 1</td>
<td>.638 (p&lt;0.001)</td>
<td>.466 (p&lt;0.010)</td>
<td>.537 (p&lt;0.002)</td>
<td>.564 (p&lt;0.001)</td>
</tr>
<tr>
<td>Lateral Femoral Cortex 2</td>
<td>.571 (p&lt;0.001)</td>
<td>.486 (p&lt;0.006)</td>
<td>.590 (p&lt;0.001)</td>
<td>.580 (p&lt;0.001)</td>
</tr>
<tr>
<td>Medial Femoral Cortex 2</td>
<td>.731 (p&lt;0.001)</td>
<td>.665 (p&lt;0.001)</td>
<td>.719 (p&lt;0.001)</td>
<td>.736 (p&lt;0.001)</td>
</tr>
<tr>
<td>Cortical Index 2</td>
<td>.614 (p&lt;0.001)</td>
<td>.467 (p&lt;0.009)</td>
<td>.543 (p&lt;0.002)</td>
<td>.565 (p&lt;0.001)</td>
</tr>
<tr>
<td>Modified Tingart Score</td>
<td>.773 (p&lt;0.001)</td>
<td>.669 (p&lt;0.001)</td>
<td>.736 (p&lt;0.001)</td>
<td>.746 (p&lt;0.001)</td>
</tr>
</tbody>
</table>
Figure 6.8 The Pearson R Correlation Values from the different Hip DXA Sites
6.28 Discussion

The results show that the simple cortical measures, cortical indices and summation of cortical measures of the proximal femur correlated well with DXA measures of the hip. These findings concur with Chappard et al. (2012), who measured the medial and lateral femoral cortices of the proximal femur and the femoral calcar (Chappard et al., 2010). Even though, their designated medial and lateral femoral cortices were different (the lateral femoral cortex was measured perpendicular to the lower end of the lesser trochanter and the medial femoral cortex was measured 3 cm below the lower end of the lesser trochanter) their correlations (medial femoral cortex vs Whole Hip DXA, \( r=0.67 \)) matched the findings reported here for the same region (\( r=0.66 \)). This would suggest that this technique is a reproducible useful measure of BMD and the findings reported here coupled with those of Chappard et al support the concept of using measures of cortical thickness as a proxy for BMD.

The use of a summation of cortical measures provided the strongest correlation with DXA, both from the results in this thesis and those of Chappard et al. (2012). One must note that Chappard et al. (2012) found very strong correlations between the femoral calcar thickness and Whole Hip DXA (\( r=0.76 \)). However assessment of this measure in the fractured proximal femur is often very difficult if not impossible. Whereas, it was possible to measure the cortices at the 4 sites described in this thesis in all of the patients. It was considered, therefore, that the summation of cortical measures, which had the best correlation with the DXA values was the preferred pre-operative assessment tool of hip BMD from digital radiographs.

The intertrochanteric DXA values were found to correlate most strongly with the cortical measures, which is in keeping with this region of the proximal femur being closest to the cortical measures assessed. However, fixation devices for proximal femoral fractures are anchored within the femoral head. Although, the correlations of the cortical thicknesses with the whole hip DXA and the femoral head DXA values were less strong they were still significant, suggesting that this technique was justified in clinical practice.
The femoral head diameter was chosen to determine the sites at which the cortical measures were obtained as this allowed for standardisation among patients of different sizes, compared to fixed measures (Chappard et al., 2010). The Tingart Score (Tingart et al., 2003) employed a cortical measuring score at the level of the proximal diaphyseal margin and then 2 cm inferior to this, in the proximal humerus. This 2 cm measure could have been used in the current study (using the aluminium step wedge for calibration), however, the step wedge may not be included routinely in the radiographs. Thus, the measure of a further half femoral head diameter was chosen, as this was a close approximation to 2 cm.

It should be noted that the cortical measurements taken from the radiographs in the present study were corrected for magnification, and these provided a statistically significant correlation with the DXA measures. When the cortical measures were not corrected for magnification, the correlation strength with DXA was notably reduced (see Appendix 4). It was possible to account for magnification given the inclusion of the step wedge, which acted as a calibration tool with its known dimensions. However, such an item may not be included in future radiographs. As such further research is required to establish a method for calculating ‘real time’ cortical measures from standard ‘clinical’ hip radiographs.

6.29 Summary

Summation of cortical measures of the proximal femur from digital hip radiographs provided the strongest correlation with hip DXA measures. Correlation was strongest with Intertrochanteric DXA values, but good with all hip DXA values. Further research is required to enable ‘real time’ cortical measures to be calculated from standard ‘clinical’ radiographs.
6.3 Assessment of the Effect of Proximal Femoral Rotation on Cortical Measures

6.31 Assessment of the Effect of Proximal Femoral Rotation on Cortical Measures

This section describes the use of CT Scans of the Hip to assess the effect of proximal femoral rotation on the cortical measures of the proximal femur, providing results to quantify the degree of rotation tolerated with the cortical measuring technique.

Hip fractures can be displaced or undisplaced (Court-Brown et al., 2006). With an undisplaced hip fracture, the injured limb lies in the neutral orientation with around 10 degrees of external rotation (Court-Brown et al., 2006). However, with a displaced hip fracture, due to the unopposed forces of the iliopsoas and hip abductor muscles, the injured limb is flexed and abducted at the hip with an increased degree of external rotation (Court-Brown et al., 2006). Such a discrepancy in the positioning of the leg could impart a considerable variation on recorded cortical measures, if the cortical measures were found to vary with rotation. The femoral diaphysis has been reported to be cylindrical (Liang et al., 2009), however little data exists regarding the variations in femoral diaphyseal cortical thickness with rotation.

To investigate the effect of proximal femoral rotation on the cortical measures of the proximal femur, a cohort of 30 patients was identified, who had CT Pelvis Scans at Royal Infirmary of Edinburgh between 2011 and 2013 to investigate suspected undisplaced proximal femoral fractures. The non-injured hip was identified and cortical measures analyses were performed on the proximal femur. These analyses were performed at the point one femoral head diameter directly inferior to the superior aspect of the lesser trochanter. It was not possible to locate the point a further half femoral head diameter beneath this region as it was not within the field of view of the CT Scan. The true medial and lateral femoral cortices were identified from their relationship to the linea aspera. Cortical measures were taken around an eighty degree arc from these measures respectively.

The process for this involved:
1. The CT Scan was uploaded onto the PACS System (see Figure 6.9).

![Figure 6.9: The CT Scan of a Hip Fracture on the PACS System](image)

2. The MPR ‘Image Analysis’ mode was activated.

3. The Coronal Image was accessed and adjusted to display the femoral head at its maximum diameter.

4. The Diameter of the Femoral Head was measured (see Figure 6.10)

![Figure 6.10: Measurement of the Femoral Head Diameter on the Coronal Image of the CT Scan of the Hip Fracture on the MPR System.](image)
5. The region one Femoral Head Diameter directly inferior to the superior aspect of the lesser trochanter on the coronal view was located (see Figure 6.11).

![Figure 6.11: Identification of the region one Femoral Head Diameter directly inferior to the superior aspect of the lesser trochanter on the coronal view of the CT Scan on the MPR System.](image1)

6. The image was transferred to the axial view at the same region (see Figure 6.12).

![Figure 6.12: One Femoral Head Diameter directly inferior to the superior aspect of the lesser trochanter on the axial view of the CT Scan on the MPR System.](image2)
7. The linea aspera was marked on the cross section of the femoral diaphysis on the axial view at this region (see Figure 6.13).

Figure 6.13: Marking of the linea aspera one Femoral Head Diameter directly inferior to the superior aspect of the lesser trochanter on the axial view of the CT Scan on the MPR System.

8. The medial and lateral femoral corticies were marked, being at 90 degrees to linea aspera respectively (see Figure 6.14).

Figure 6.14: Marking of the medial and lateral femoral cortices one Femoral Head Diameter directly inferior to the superior aspect of the lesser trochanter on the axial view of the CT Scan on the MPR System.
9. The width of the lateral femoral cortex was measured (see Figure 6.15).

![Figure 6.15: Measuring the width of the lateral femoral cortex one Femoral Head Diameter directly inferior to the superior aspect of the lesser trochanter on the axial view of the CT Scan on the MPR System.](image1)

10. The width of the cortices 10, 20, 30, 40 degrees clockwise and anticlockwise respectively from the lateral cortex was measured. (see Figure 6.16)

![Figure 6.16: Measuring the width of the cortices 10, 20, 30, 40 degrees clockwise and anticlockwise respectively from the lateral cortex one Femoral Head Diameter directly inferior to the superior aspect of the lesser trochanter on the axial view of the CT Scan on the MPR System.](image2)
11. The width of the medial femoral cortex was measured (see Figure 6.17).

6.17: Measuring the width of the medial femoral cortex one Femoral Head Diameter directly inferior to the superior aspect of the lesser trochanter on the axial view of the CT Scan on the MPR System.

12. The width of the cortices 10, 20, 30, 40 degrees clockwise and anticlockwise respectively from the medial cortex was measured. (see Figure 6.18).

6.18: Measuring the width of the cortices 10, 20, 30, 40 degrees clockwise and anticlockwise respectively from the medial cortex one Femoral Head Diameter directly inferior to the superior aspect of the lesser trochanter on the axial view of the CT Scan on the MPR System.
13. The percentage variation for each of these cortices from the respective medial or lateral femoral cortex was calculated with the following equation:

\[
\text{Percentage Variation: } \frac{\text{Cortical Measure} - \text{Respective Medial or Lateral Femoral Cortex}}{\text{Respective Medial or Lateral Femoral Cortex}} \times 100
\]

This allowed assessment of the cortical measures within an 80 degrees arc of rotation from the medial and lateral cortices respectively. This accounted for 40 degrees rotation in either direction.

The Percentage Variation Graphs for the cortical measures are shown in Figure 6.19 and Figure 6.20.

![Variation with Rotation at Lateral Femoral Cortex](image)

Figure 6.19: The Percentage Variation of Cortical Values with Rotation from the Lateral Femoral Cortex.
6.32 Discussion

The mean variation ranged from two to seven percent for an arc of 80 degrees around the medial and lateral femoral cortices with a maximum variation of eleven percent. For a reading of 11mm this would equate to a mean error of 0.6mm and a maximum 1.1mm error. The figure of 40 degrees was chosen as a previous study had found the mean and standard deviation of rotation of neck of femur fractures to lie within 36 degrees (Marmor et al., 2012). 0.6mm was considered to be an acceptable error in the technique, accounting for a maximum of 10% error in the cortical readings (see Figures 6.19 and 6.20). Comparing this against previous literature, Liang et al. (2009) reported that the femoral diaphysis was cylindrical. From a cadaver study with 112 proximal femoral specimens, they found that the mean anterior-posterior diameter of the femoral diaphysis 5 cm below lesser trochanter was 26.0mm, and the mean medial-lateral diameter of the femoral diaphysis 5 cm below
lesser trochanter was 26.4mm. However they did not investigate the variation in femoral diaphyseal cortical thickness with rotation.

6.33 Summary
The variation imposed on femoral diaphyseal cortical measures by proximal femoral rotation in hip fractures was considered to be within acceptable limits justifying the use of cortical measures in hip radiographs for pre-operative assessment of hip BMD in clinical practice.
6.4 Cortical Measures in the Wrist Radiographs

This section provides the results of the analyses of the cortical measures of the 2nd metacarpal and the radial and ulna diaphyses from the PA wrist radiographs and correlates them with the DXA measures from the Forearm and from the Hip.

The cortical measures taken for the PA wrist radiographs included the width of the radial mid-diaphyseal cortex of the 2nd metacarpal, the width of the ulnar mid-diaphyseal cortex of the 2nd metacarpal, the width of the radial cortex of the distal radial diaphysis, the width of the ulnar cortex of the distal radial diaphysis, the width of the radial cortex of the distal ulna diaphysis and the width of the ulnar cortex of the distal ulna diaphysis.

The width of the mid-diaphysis of the 2nd metacarpal, the width of the distal radial diaphysis and the width of the distal ulna diaphysis were also measured to allow the calculation of respective Cortical Indices. Lastly the radial and ulna cortical measures and the radial and 2nd metacarpal cortical measures were summed to given combined cortical scores. These are described in the sections below.

In comparison to the hip radiographs, the degree of rotation of the distal radius and ulna was minimal, as the deforming forces seen in the fractured hip, do not occur in the fractured wrist.
6.41 The Width of the Radial Mid-Diaphyseal Cortex of the 2nd Metacarpal in the PA Wrist Radiograph

This section describes the results obtained for the width of the radial mid-diaphyseal cortex of the 2nd metacarpal in the PA wrist radiograph and its correlations with the Forearm and Hip DXA results.

The process of performing this measurement is detailed in Chapter 4.38.

The Correlation Graphs between the DXA values of the forearm and this cortical measure are shown in Figure 6.21.

![Graphs showing correlations between 2nd MCP Radial Cortex and DXA values](image)

**Figure 6.21:** Correlation between the Radial Cortex of the 2nd Metacarpal and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Mid-Distal Region provided the strongest correlation with this cortical measure (see Figure 6.32).
6.42 The Width of the Ulnar Mid-Diaphyseal Cortex of the 2nd Metacarpal in the PA Wrist Radiograph

This section describes the results obtained for the width of the ulnar mid-diaphyseal cortex of the 2nd metacarpal, in the PA wrist radiograph and its correlations with the Forearm and Hip DXA results.

The process of performing this measurement is detailed in Chapter 4.38.

The Correlation Graphs between the DXA values of the forearm and this cortical measure are shown in Figure 6.22.

![Graphs showing correlations between Ulnar Cortex and DXA values](image)

Figure 6.22: Correlation between the Ulnar Cortex of the 2nd Metacarpal and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Proximal Region provided the strongest correlation with this cortical measure (see Figure 6.32).
6.43 The Cortical Index of the Mid-Diaphysis of the 2\textsuperscript{nd} Metacarpal in the PA Wrist Radiograph

This section describes the results obtained for the Cortical Index of the mid-diaphysis of the 2\textsuperscript{nd} metacarpal in the PA wrist radiograph and its correlations with Forearm and Hip DXA.

The process of performing this measurement is detailed in Chapters 4.38 and 6.23.

The Correlation Graphs between the DXA values of the forearm and this Cortical Index are shown in Figure 6.23.

![Correlation Graphs](image)

Figure 6.23: Correlation between the Cortical Index of the 2\textsuperscript{nd} Metacarpal and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Proximal Region provided the strongest correlation with this Cortical Index (see Figure 6.32).
6.44 The Width of the Radial Cortex of the Radial Diaphysis in the PA Wrist Radiograph

This section describes the results obtained for the width of the radial cortex of the radial diaphysis 2 widths of the distal radial articular surface proximally from the mid point of the distal radial articular surface in the PA Wrist Radiograph and its correlations with the Forearm and Hip DXA results.

The process of performing this measurement is detailed in Chapter 4.39.

The Correlation Graphs between the DXA values of the forearm and this cortical measure are shown in Figure 6.24.

![Correlation Graphs](image)

Figure 6.24: Correlation between the Radial Cortex of the Radial Diaphysis and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Ultra Distal Region provided the strongest correlation with this cortical measure (see Figure 6.32).
6.45 The Width of the Ulnar Cortex of the Radial Diaphysis in the PA Wrist Radiograph

This section describes the results obtained for the width of the ulnar cortex of the radial diaphysis 2 widths of the distal radial articular surface proximally from the mid point of the distal radial articular surface in the PA Wrist Radiograph and its correlations with the Forearm and Hip DXA results.

The process of performing this measurement is detailed in Chapter 4.39. The Correlation Graphs between the DXA values of the forearm and this cortical measure are shown in Figure 6.25.

![Correlation Graphs](image)

Figure 6.25: Correlation between the Ulnar Cortex of the Radial Diaphysis and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Ultra Distal Region provided the strongest correlation with this cortical measure (see Figure 6.32).
6.46 The Cortical Index of the Radial Diaphysis in the PA Wrist Radiograph

This section describes the results obtained for the Cortical Index of the radial diaphysis 2 widths of the distal radial articular surface proximally from the midpoint of the distal radial articular surface in the PA Wrist Radiograph and its correlations with Forearm and Hip DXA.

The process of performing this measurement is detailed in Chap 4.39 and 6.23. The Correlation Graphs between the DXA values of the forearm and this Cortical Index are shown in Figure 6.26.

Figure 6.26: Correlation between the Cortical Index of the Radial Diaphysis and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Ultra Distal Region provided the strongest correlation with this Cortical Index (see Figure 6.32).
6.47 The Width of the Radial Cortex of the Ulnar Diaphysis in the PA Wrist Radiograph

This section describes the results obtained for the width of the radial cortex of the ulnar diaphysis 2 widths of the distal radial articular surface proximally from the midpoint of the distal radial articular surface in the PA Wrist Radiograph and its correlations with the Forearm and Hip DXA results.

The process of performing this measurement is detailed in Chap 4.40. The Correlation Graphs between the DXA values of the forearm and this cortical measure are shown in Figure 6.27.

Figure 6.27: Correlation between the Radial Cortex of the Ulnar Diaphysis and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Proximal Region provided the strongest correlation with this cortical measure (see Figure 6.32).
The Width of the Ulnar Cortex of the Ulnar Diaphysis in the PA Wrist Radiograph

This section describes the results obtained for the width of the ulnar cortex of the ulnar diaphysis 2 widths of the distal radial articular surface proximally from the midpoint of the distal radial articular surface in the AP Wrist Radiograph and its correlations with the Forearm and Hip DXA results.

The process of performing this measurement is detailed in Chap 4.40. The Correlation Graphs between the DXA values of the forearm and this cortical measure are shown in Figures 6.28.

Figure 6.28: Correlation between the Ulnar Cortex of the Ulnar Diaphysis and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Whole Forearm Region provided the strongest correlation with this cortical measure (see Figure 6.32).
6.49 The Cortical Index of the Ulnar Diaphysis in the PA Wrist Radiograph

This section describes the results obtained for the Cortical Index of the ulnar diaphysis 2 widths of the distal radial articular surface proximally from the midpoint of the distal radial articular surface in the PA Wrist Radiograph and its correlations with Forearm and Hip DXA.

The process of performing this measurement is detailed in Chap 4.40 and 6.23. The Correlation Graphs between the DXA values of the forearm and this Cortical Index are shown in Figure 6.29.

Figure 6.29: Correlation between the Cortical Index of the Ulnar Diaphysis and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Ultra-Distal Region provided the strongest correlation with this Cortical Index (see Figure 6.32).
6.50 The Combined Radius and 2\textsuperscript{nd} Metacarpal Score

This section describes the results obtained for the Combined Radius and 2\textsuperscript{nd} Metacarpal Score in the PA Wrist Radiograph and its correlations with Forearm and Hip DXA.

The combined Radius and 2\textsuperscript{nd} Metacarpal Score was created using the formula:

Combined Radius and 2\textsuperscript{nd} Metacarpal Score = a+b+c+d

\[ a = \text{Radial Cortex of the Distal Radial Diaphysis (see Chapter 6.44)} \]
\[ b = \text{Ulnar Cortex of the Distal Radial Diaphysis (see Chapter 6.45)} \]
\[ c = \text{Radial Cortex of the 2\textsuperscript{nd} Metacarpal Mid-Diaphyseal (see Chapter 6.41)} \]
\[ d = \text{Ulnar Cortex of the 2\textsuperscript{nd} Metacarpal Mid-Diaphyseal (see Chapter 6.42)} \]
The Correlation Graphs between the DXA values of the forearm and this cortical score are shown in Figure 6.30.

![Graphs showing correlation between Combined Radius & 2nd MCP Score vs Ultra Distal DXA, Mid Distal DXA, Proximal DXA, and Whole Forearm DXA](image)

Figure 6.30: Correlation between the Combined Radius & 2nd Metacarpal Score and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Ultra-Distal Region provided the strongest correlation with this cortical score (see Figure 6.32).

6.51 The Combined Radius and Ulna Score

This section describes the results obtained for the combined Radius and Ulna Score in the PA Wrist Radiograph and its correlations with Forearm and Hip DXA.

The combined Radius and Ulna was created using the following formula:

\[
\text{Combined Radius and Ulna Score} = a + b + c + d
\]
a= Radial Cortex of the Distal Radial Diaphysis (see Chapter 6.44)
b= Ulnar Cortex of the Distal Radial Diaphysis (see Chapter 6.45)
c= Radial Cortex of the Distal Ulnar Diaphysis (see Chapter 6.47)
d= Ulnar Cortex of the Distal Ulnar Diaphysis (see Chapter 6.48)

The Correlation Graphs between the DXA values of the forearm and this cortical score are shown in Figure 6.31.

Figure 6.31: Correlation between the Combined Radius & Ulna Score and: a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

The Pearson R Correlation values for forearm and hip DXA values are in Table 6.2. The DXA Values from the Ultra-Distal Region provided the strongest correlation with this cortical measure (see Figure 6.32).
Table 6.2: The Pearson R Correlation Values between the Forearm Cortical Measures and the Forearm and Hip DXA Values

<table>
<thead>
<tr>
<th>Pearson R Correlation</th>
<th>Ultra-Distal</th>
<th>Mid-Distal</th>
<th>Proximal</th>
<th>Forearm</th>
<th>Hip</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd MCP Radial Cortex</td>
<td>.557 (p=0.120)</td>
<td>.704 (p&lt;0.034)</td>
<td>.622 (p=0.074)</td>
<td>.659 (p=0.053)</td>
<td>.276 (p=0.203)</td>
</tr>
<tr>
<td>2nd MCP Ulnar Cortex</td>
<td>.037 (p=0.925)</td>
<td>.195 (p=0.615)</td>
<td>.298 (p=0.436)</td>
<td>.175 (p=0.652)</td>
<td>.278 (p=0.199)</td>
</tr>
<tr>
<td>2nd MCP Cortical Index</td>
<td>.608 (p=0.083)</td>
<td>.602 (p=0.086)</td>
<td>.535 (p=0.138)</td>
<td>.593 (p=0.092)</td>
<td>.415 (p=0.049)</td>
</tr>
<tr>
<td>Radial Diaphysis Radial Cortex</td>
<td>.617 (p=0.077)</td>
<td>.507 (p=0.164)</td>
<td>.508 (p=0.163)</td>
<td>.538 (p=0.135)</td>
<td>.240 (p=0.271)</td>
</tr>
<tr>
<td>Radial Diaphysis Ulnar Cortex</td>
<td>.356 (p=0.347)</td>
<td>.251 (p=0.514)</td>
<td>.223 (p=0.564)</td>
<td>.258 (p=0.502)</td>
<td>.116 (p=0.600)</td>
</tr>
<tr>
<td>Radial Diaphysis Cortical Index</td>
<td>.508 (p=0.163)</td>
<td>.439 (p=0.238)</td>
<td>.426 (p=0.253)</td>
<td>.448 (p=0.226)</td>
<td>.327 (p=0.128)</td>
</tr>
<tr>
<td>Ulnar Diaphysis Radial Cortex</td>
<td>.739 (p&lt;0.023)</td>
<td>.736 (p&lt;0.024)</td>
<td>.816 (p&lt;0.007)</td>
<td>.781 (p&lt;0.013)</td>
<td>.084 (p=0.705)</td>
</tr>
<tr>
<td>Ulnar Diaphysis Ulnar Cortex</td>
<td>.751 (p&lt;0.020)</td>
<td>.753 (p&lt;0.019)</td>
<td>.720 (p&lt;0.029)</td>
<td>.767 (p&lt;0.016)</td>
<td>.018 (p=0.935)</td>
</tr>
<tr>
<td>Ulnar Diaphysis Cortical Index</td>
<td>.763 (p&lt;0.017)</td>
<td>.691 (p&lt;0.039)</td>
<td>.720 (p&lt;0.029)</td>
<td>.736 (p&lt;0.024)</td>
<td>.227 (p=0.297)</td>
</tr>
<tr>
<td>Radial and Ulnar Score</td>
<td>.673 (p&lt;0.047)</td>
<td>.594 (p=0.092)</td>
<td>.588 (p=0.096)</td>
<td>.618 (p=0.076)</td>
<td>.085 (p=0.701)</td>
</tr>
<tr>
<td>Radial and 2nd MCP Score</td>
<td>.462 (p=0.210)</td>
<td>.431 (p=0.247)</td>
<td>.418 (p=0.263)</td>
<td>.432 (p=0.246)</td>
<td>.243 (p=0.264)</td>
</tr>
</tbody>
</table>
Figure 6.32 The Pearson R Correlation Values from the different DXA Sites
6.52 Discussion

The results demonstrated that the simple cortical measures, cortical indices and summation of cortical measures of the distal radius, distal ulna and second metacarpal provided variable, often poor, correlations with DXA measures of the forearm and the hip. There was limited data available against which to compare these results from the radius and ulna. Meema et al (1965) reported that cortical measures of the proximal radius (just distal to the radial tuberosity) were noted to decrease with age, female gender and following the menopause but they were unable to make comparisons with formal BMD measures.

Use of cortical measures of the second metacarpal as an assessment of BMD has been better studied (Barnett and Nordin, 1960, Wishart et al., 1993). Barnett and Nordin (1970) found that the 2nd metacarpal cortical index decreased with age and was notably lower in patients with clinically suspected osteoporosis compared to a control group. However, they noted a high risk for error in this measure due to the limited dimensions of the metacarpus, and again could not validate this measure against formal BMD results. Wishart et al. (1993) found that the 2nd metacarpal cortical index was correlated with vertebral DXA readings and forearm single photon absorptiometry readings, however did not make comparisons against forearm DXA readings.

None of these studies (Meema et al., 1965, Barnett and Nordin, 1960, Wishart et al., 1993) assessed the effect of summation of cortical measures on the improvement of such a technique to estimate BMD. The results from this thesis have demonstrated that this failed to improve correlations with DXA.

There was considerable variation in the site of DXA which provided the strongest correlation against the cortical measures, though in all, the Ultra-Distal DXA values most commonly correlated strongest with the cortical measures. This was surprising as the cortical measures of the radius and ulna were closer to the proximal regions of the DXA Scan. However, this is in keeping with the variable nature of the results from this section. Such inaccuracies were likely a consequence of the error incurred in this by the size of the measures made (Barnett and Nordin, 1960, Wishart et al., 1993).
Given that the correlations between the forearm cortical measures and the Hip DXA values are notably weaker than the correlations between the forearm cortical measures and the forearm DXA values, this suggests that use of the forearm cortical measures possesses a limited degree of predicting bone mineral density in this region. However due to its variability and propensity to error, we do not feel this technique should be recommended for use in clinical practice.

It was decided to use the width of the distal radial articular surface to determine the site of the radial and ulnar diaphyseal measures as this allowed for standardisation among patients. A distance of two widths was employed for this technique as this ensured the measurement was made within the diaphysis of the bone. On the majority of the radiographs, it was not possible to make further measures a standard distance proximal to this, owing to limited visualisation of the radial and ulnar diaphyses. As such it was not possible to employ a similar technique as that described by Tingart et al. (2003) in this region.

To note, the cortical measurements taken from the radiographs in the present study were corrected for magnification. It was possible to account for magnification given the inclusion of the step wedge, which acted as a calibration tool with its known dimensions. However, such an item may not be included in future radiographs. As such further research is required to establish a method for calculating ‘real time’ cortical measures from standard ‘clinical’ hip radiographs.

6.53 Summary

Cortical measures from the 2nd metacarpal, radial and ulnar diaphyses on PA wrist radiographs provided variable correlations with DXA measures of the forearm and the hip, ranging from poor to good. Correlation was strongest with Ultra Distal DXA values, but again this was variable. This technique was not recommended for use in clinical practice.
Part VII

Use of Trabecular Patterns in the Digital Radiographs to assess Bone Mineral Density
Use of Trabecular Patterns in the Digital Radiographs to assess Bone Mineral Density

7.1 The Singh Index

This section described the Singh Index and its use in BMD assessment.

The Singh Index is a six point grading system which defines BMD from hip radiographs through assessment of the presence of compressive and tensile trabeculae at the proximal femur (Singh et al., 1970).

Previous studies have shown it to correlate with proxy measures of BMD such as age and gender, histological osteoporosis grading of iliac crest bone samples (Singh et al., 1970) and dry ash bone weight of the femoral head (Cooper et al., 1986). However, further studies have found it to correlate poorly correlation with DXA measures (Koot et al., 1996).

All these studies were performed with plain AP Pelvic radiographs. As such, there has been no assessment of the role that digital radiography can take to improve the accuracy of this technique and enhance its correlation with DXA assessment of BMD. Such improvements could be made through the use of the contrast enhancing and magnification tools present on the digital system, as well as the image processing that takes place prior to electronic publication of the radiographs on PACS. Further to this, a more limited grouping of the Singh Index may also improve the correlation with DXA measures, yet this has still to be fully assessed.
7.2 Methods

This section describes the methods used for this part of the study.
Of the thirty-seven patients from the hip fracture cohort who underwent DXA scanning, there were thirty that had adequate AP Pelvic Radiographs to allow Singh Index assessment of the uninjured hip.

The acquisition and processing of these radiographs is described in Chapters 3.1 and 4.1. The analysis of these radiographs to allow for Singh Index assessment is described in Chapter 4.10.

Singh Index Assessment was performed on the FUJI Radiographs (via the Image J System) and on the PACS Radiographs (via the PACS System): for both sets of radiographs, Singh Index Assessment was performed on the ‘Original’ radiographs, the ‘Inverted’ radiographs and the ‘Contrast-Enhanced’ radiographs.

Singh Index Assessment was performed three times with each mode of assessment on the two sets of radiographs, with intra-observer reliability calculated for each.

Singh Index Values were compared with the relevant DXA measures using the Pearson R correlation model. The initial correlation was performed using the six grades. A further assessment was performed when grouping the grades into two cohorts (Grades 1-3) and (Grades 4-6). A Student T test was performed to assess for a significant association between the DXA values and these Singh divisions.
7.3 The Use of the Digital Radiographic Tools to Improve the Accuracy of the Singh Index

This section describes the results from the use of the digital radiographic tools to improve the accuracy of the Singh Index.

The initial Singh Index values from analysis of the PACS radiographs and the FUJI radiographs (via Image J analysis) are given in Figure 7.1. The Singh Index Values from inverted image analysis of the PACS radiographs and the FUJI radiographs (via Image J analysis) are given in Figure 7.1. The final Singh Index Values from digital tool enhanced analysis of the PACS radiographs and the FUJI radiographs (via Image J analysis) are given in Figure 7.1.

There was no difference in Singh Index values between the initial PACS and FUJI radiographs. Image inversion failed to improve the accuracy of the Singh Index. Contrast enhancement with the FUJI radiographs (via Image J analysis) improved the accuracy of the Singh Index but not with the PACS radiographs.

![The Effect of Digital Enhancement on Singh Index](image)

Figure 7.1: The Effect of Digital Enhancement on Singh Index Assessment.

Intra-Observer reliability for all techniques was excellent (r=0.89; 95%CI 0.85-0.93).
7.4 The Correlation of the Singh Index with Hip DXA

7.41 The Correlation of the Singh Index with Different Hip DXA Sites

This section describes the correlations results obtained between the Singh Index Values and the Hip DXA Values.

The Correlation Graphs between the Singh Index values from the Original PACS radiographs and the different sites of Hip DXA are shown in Figure 7.2.

![Singh Index vs Intertrochanteric DXA](image1)

![Singh Index vs Femoral Neck DXA](image2)

![Singh Index vs Trochanteric DXA](image3)

![Singh Index vs Whole Hip DXA](image4)

Figure 7.2: Correlation between the Singh Index and: a) Intertrochanteric DXA; b) Femoral Neck DXA; c) Trochanteric DXA; d) Whole Hip DXA.

The Pearson R Correlation values are provided in Table 7.1.

The DXA Values from the Intertrochanteric Region provided the strongest correlation with the Singh Index (see Figure 6.8).
Table 7.1: The Pearson R Correlation Values between the Singh Index and Hip DXA

<table>
<thead>
<tr>
<th>Pearson R Correlation</th>
<th>Intertrochanteric</th>
<th>Femoral Neck</th>
<th>Trochanteric</th>
<th>Whole Hip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singh Index</td>
<td>.243 (p=0.197)</td>
<td>.194 (p=0.304)</td>
<td>.197 (p=0.296)</td>
<td>.196 (p=0.298)</td>
</tr>
</tbody>
</table>

7.42 The Effect of Image Processing on the Correlation between the Singh Index and Hip DXA

The Correlation Graphs between the Singh Index Values from the ‘Original’ PACS and ‘Original’ Image J radiographs and the whole Hip DXA are shown in Figure 7.3.

![Correlation Graphs](image.png)

Figure 7.3: Correlation between the Singh Index and Hip DXA for: a) the ‘Original’ PACS Images; b) the ‘Original’ Image J Images.

The Correlation Graphs between the Singh Index Values from the ‘Inverted’ PACS and ‘Inverted’ Image J radiographs and the whole Hip DXA are shown in Figure 7.4.

![Correlation Graphs](image.png)

Figure 7.4: Correlation between the Singh Index and Hip DXA for: a) the ‘Inverted’ PACS Images; b) the ‘Inverted’ Image J Images.
The Correlation Graphs between the Singh Index Values from the ‘Contrast-Enhanced’ PACS and ‘Contrast-Enhanced’ Image J radiographs and the whole Hip DXA are shown in Figure 7.5.

Figure 7.5: Correlation between the Singh Index and Hip DXA for: a) the ‘Contrast-Enhanced’ PACS Images; b) the ‘Contrast-Enhanced’ Image J Images.

The Pearson R Correlation values are provided in Table 7.2.

The Singh Index Values from the ‘Contrast-Enhanced’ Image J Images provided the strongest correlation with the Hip DXA values.

Table 7.2: The Pearson R Correlation Values between the Singh Index and Hip DXA – The Effects of the Digital Enhancement Tools

<table>
<thead>
<tr>
<th>Singh Index vs Whole Hip DXA</th>
<th>Pearson R Co-Efficient</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PACS Original</td>
<td>.196</td>
<td>0.298</td>
</tr>
<tr>
<td>PACS Inverted</td>
<td>.196</td>
<td>0.298</td>
</tr>
<tr>
<td>PACS Contrast-Enhanced</td>
<td>.196</td>
<td>0.298</td>
</tr>
<tr>
<td>Image J Original</td>
<td>.196</td>
<td>0.298</td>
</tr>
<tr>
<td>Image J Inverted</td>
<td>.196</td>
<td>0.298</td>
</tr>
<tr>
<td>Image J Contrast-Enhanced</td>
<td>.283</td>
<td>0.130</td>
</tr>
</tbody>
</table>
Using the Singh Index values from the ‘Original’ PACS radiographs and grouping them into two categories (Singh Index 1 to 3 and Singh Index 4 to 6), there was no significant association between Singh Index and whole Hip DXA (p=0.220).

Using the Singh Index values from the ‘Contrast-Enhanced’ Image J radiographs and grouping them into two categories (Singh Index 1 to 3 and Singh Index 4 to 6), there was no significant association between Singh Index and whole Hip DXA (p=0.188).

Grouping the patients into the three categories: ‘normal BMD’ (T-Score ≤ 1.0), ‘osteopenic’ (T-Score between 1.0 and 2.5) and ‘osteoporotic’ (T-Score ≥ 2.5), there was no significant association between the category of BMD from the whole Hip DXA and the Singh Index Values from the ‘Original’ PACS radiographs (p=0.432)

7.5 Discussion

No significant correlation between the Singh Index Values (PACS and Image J – ‘Original’ and ‘Inverted’) and the Hip DXA values was found. An improved correlation was observed between the Singh Index values and the Hip DXA results, following contrast enhancement of the FUJI radiographs using the Image J system, but not following contrast enhancement of the PACS radiographs. The improved correlation was however not statistically significant.

Previous studies have similarly reported poor correlation between the Singh Index and hip DXA values(Koot et al., 1996). While the Singh Index initially appeared a promising indicator of osteoporosis due to its correlations with measures of BMD (age and gender, histological osteoporosis grading of iliac crest bone samples and dry ash bone weight of the femoral head)(Singh et al., 1970, Cooper et al., 1986), it appears to be a poor predictor of DXA BMD measures. As such its use as a pre-operative measure of BMD was not advocated from the results of this study.
Similar shortcomings in this technique include poor interobserver reliability however this was not examined in the current study (Koot et al., 1996).

It was interesting to note that contrast enhancement of the FUJI Radiographs with the Image J system improved the correlation between the Singh Index and hip DXA values but contrast enhancement with the PACS system did not. This may have been due to the Automatic Gain Control image processing of the PACS radiographs which prevented further true textural enhancement of the images with the contrast tools (Nomoto et al., 2008).

7.6 Summary

In summary, it appeared that the Singh Index failed to provide an effective pre-operative measure of BMD. Contrast enhancement with the digital system improved Singh Index definition in non-processed radiographs; however even this still failed to provide an effective pre-operative measure of BMD.
Part VIII

Use of Aluminium Equivalent Grading in the Digital Radiographs to assess Bone Mineral Density
Use of Aluminium Equivalent Grading in the Digital Radiographs to assess Bone Mineral Density

8.1 Introduction

Use of an aluminium step wedge in plain radiographs to establish aluminium equivalent density values has been well established in the field of dentistry (Watts and McCabe, 1999, ISO and 1998, ISO, 2000, ISO, 2001), and has also been validated in other fields such as archaeology (Symmons, 2004). Use of this technique in digital radiography has only recently been assessed, but again has been validated in the field of dentistry (Nomoto et al., 2008). Use of this technique as a method to estimate BMD in the human limb has been limited, due to difficulties in accounting for the effects of soft tissue attenuation, as well as various other factors (Dawson, 2009). This however has been addressed at a recent PhD at our institution (Dawson, 2009), and as such the aim of the current study was to assess the accuracy of this technique to assess BMD at the proximal femur and distal radius in the clinical cohort studied in this thesis.

8.2 Methods

This section describes the methods used in this section of the study.

Of the 50 patients within the hip fracture cohort, there were 32 that had adequate AP and Lateral Hip Radiographs to allow aluminium equivalent estimation of the proximal femur. Of the 52 patients within the wrist fracture cohort, there were 23 that had adequate PA and Lateral Wrist Radiographs to allow aluminium equivalent estimation of the distal radius. The acquisition and processing of these radiographs is described in Chapters 3.1, 3.2, and 4.1. The method by which the aluminium step wedge was included in the AP radiographs of the Hip and the PA radiographs of the Wrist has been described in Chapters 3.1 and 3.2. The method by which the thickness of the soft tissue and bone
of these regions was assessed has been described in Chapters 4.5 and 4.7. The process required for X-ray download and transfer to Edinburgh University Orthopaedic Engineering laboratory for the MatLab analysis has been described in Chapters 3.1, 3.2 and 4.1. The technique and equations for the MatLab analysis have been described in Chapters 4.11 and 4.12.

The region chosen for analysis of the proximal femur on the MatLab programme was that of the proximal metaphyseal region at the level of the lesser trochanter (see Figure 8.1a). This allowed establishment of a corresponding point on the lateral radiograph to ascertain the soft tissue and bone thickness measurements at this region (see Figure 8.1b). Given the fracture types present in the study, with none extending distal to the lesser trochanter, this also prevented the fracture from interfering with the analysis. The results from this region were compared against all four values of the Hip DXA analysis; it was hypothesised that the correlation with the aluminium measures would be strongest with the Intertrochanteric Values as this was closest to the ROI.

![Figure 8.1: a) The ROI for the Aluminium Equivalent Values in the AP Hip Radiographs; b) Corresponding Soft Tissue Measurement in the Lateral Hip Radiographs.](image)
The region chosen for analysis of the distal radius on the MatLab programme was that at the level of the distal metaphyseal region (see Figure 8.2a). This allowed establishment of a corresponding point on the lateral radiograph to ascertain the soft tissue and bone thickness measurements at this region (see Figure 8.2b). Given the fracture types present in the study, with none extending proximal to the distal metaphysis, this prevented the fracture from interfering with the analysis. This was compared against all four values of the Forearm DXA analysis and the Hip DXA analysis; it was hypothesised that the correlation with the aluminium measures would be strongest with the Ultra Distal Values as this was closest to the ROI.

Figure 8.2: a) The ROI for the Aluminium Equivalent Values in the PA Wrist Radiographs; b) Corresponding Soft Tissue Measurement in the Lateral Wrist Radiographs.
8.3 Results for the Hip Radiographs

This section describes the results obtained for the aluminium equivalent measures of the proximal femur in the AP Hip Radiograph and its correlations with DXA.

8.31 Soft Tissue and Bone Thickness Values from the Hip Radiographs

The values for the soft tissue and bone thickness of the Hip Radiographs are given in Table 8.1.

Table 8.1: The Soft Tissue and Bone Thickness Values for the Hip and Wrist Radiographs

<table>
<thead>
<tr>
<th></th>
<th>Hip Radiographs</th>
<th>Wrist Radiographs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone Thickness (Range: SD) (mm)</td>
<td>35.9 (30.7 - 43.8: 3.0)</td>
<td>10.7 (8.8 - 11.3: 0.7)</td>
</tr>
<tr>
<td>Total Soft Tissue Thickness (Range: SD) (mm)</td>
<td>107.7 (52.3 - 143.1: 19.9)</td>
<td>41.7 (29.7 - 46.6: 3.7)</td>
</tr>
<tr>
<td>Anterior Soft Tissue Thickness (Range: SD) (mm)</td>
<td>51.1 (9.9 - 81.4: 14.6)</td>
<td>21.0 (15.3 - 23.7: 1.9)</td>
</tr>
<tr>
<td>Posterior Soft Tissue Thickness (Range: SD) (mm)</td>
<td>56.7 (30.7 - 83.9: 14.2)</td>
<td>20.7 (14.4 - 23.4: 2.0)</td>
</tr>
</tbody>
</table>

There was considerable variation in the soft tissue thickness of the hip patients: the thinnest patient recorded a total soft tissue thickness of 52mm and the largest patient recorded a total soft tissue thickness of 143 mm. Bone thickness showed less variation with values ranging from 31mm to 44mm.
8.32 Non-Perspex Corrected Aluminium Equivalent Measures of the Proximal Femur

The aluminium equivalent density measures of the proximal femur, uncorrected for the Perspex jig, are listed in Table 8.2.

Table 8.2: The Aluminium Equivalent Measures of the Proximal Femur and the Distal Radius

<table>
<thead>
<tr>
<th></th>
<th>Proximal Femur Non-Perspex Corrected (n=32)</th>
<th>Proximal Femur Perspex Corrected (n=32)</th>
<th>Distal Radius (n=23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium Equivalent (AlEq/mm²)</td>
<td>0.79</td>
<td>1.11</td>
<td>1.20</td>
</tr>
<tr>
<td>(Range: SD)</td>
<td>(0.19 – 1.45: 0.30)</td>
<td>(0.10 – 2.08: 0.57)</td>
<td>(0.91 – 1.58: 0.19)</td>
</tr>
</tbody>
</table>

The Correlation Graphs between the Hip DXA values and the ‘Non Perspex-Corrected’ aluminium equivalent density measures of the proximal femur are shown in Figure 8.3.
Figure 8.3: Correlation between the ‘Non Perspex-Corrected’ Aluminium Equivalent Values of the Proximal Femur and: a) Intertrochanteric DXA; b) Femoral Neck DXA; c) Trochanteric DXA; d) Whole Hip DXA.

The Pearson R Correlation values are provided in Table 8.3.

The DXA Values from the Intertrochanteric Region provided the strongest correlation with this aluminium equivalent measure (see Figure 6.8).
8.33 Perspex Corrected Aluminium Equivalent Measures of the Proximal Femur

The aluminium equivalent density measures of the proximal femur, corrected for the Perspex jig, are listed in Table 8.2.

The Correlation Graphs between the Hip DXA values and the ‘Perspex-Corrected’ aluminium equivalent density measures of the proximal femur are shown in Figure 8.4.

The Pearson R Correlation values are provided in Table 8.3.

The DXA Values from the Intertrochanteric Region provided the strongest correlation with this cortical measure (see Figure 6.8).
Table 8.3: The Pearson R Correlation Values between the Proximal Femoral Aluminium Equivalent Measures and Hip DXA

<table>
<thead>
<tr>
<th>Pearson R Correlation</th>
<th>Intertrochanteric</th>
<th>Femoral Neck</th>
<th>Trochanteric</th>
<th>Whole Hip</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlEq (Perspex Corrected)</td>
<td>.345 (p=0.067)</td>
<td>.114 (p=0.557)</td>
<td>.074 (p=0.704)</td>
<td>.083 (p=0.667)</td>
</tr>
<tr>
<td>AlEq (Non Perspex Corrected)</td>
<td>.309 (p=0.103)</td>
<td>.037 (p=0.850)</td>
<td>.036 (p=0.855)</td>
<td>.057 (p=0.767)</td>
</tr>
</tbody>
</table>

8.34 Summary

Initial correlations between the aluminium equivalent measures of the proximal femur and the Hip DXA values were poor. Correction for the Perspex jig resulted in an increased correlation between the aluminium equivalent values of the proximal femur and the Hip DXA values, however the correlation still remained poor. This was likely a reflection of the considerable variation introduced into the process by the positioning of the wedge, the scatter phenomenon, the magnification in the radiographs and the inaccuracies regarding soft tissue calculation and calibration (Dawson, 2009).
8.4 Results for the Wrist Radiographs

This section describes the results obtained for the aluminium equivalent measures of the distal radius in the PA Wrist Radiograph and its correlations with Forearm and Hip DXA.

8.41 Soft Tissue and Bone Thickness Values from the Wrist Radiographs

The values for the soft tissue and bone thickness of the Wrist Radiographs are given in Table 8.1.

There was considerably less variation in the soft tissue thickness of the wrist patients compared to the hip patients: the thinnest patient recorded a total soft tissue thickness of 30 mm and the largest patient recorded a total soft tissue thickness of 47 mm. Bone thickness also showed less variation with values ranging from 9 mm to 11 mm.
8.42 Aluminium Equivalent Measures of the Distal Radius

The aluminium equivalent density measures of the distal radius are listed in Table 8.2.

The Correlation Graphs between the Forearm DXA values and the aluminium equivalent density measures of the distal radius are shown in Figure 8.5.

Figure 8.5: Correlation between the Aluminium Equivalent Values of the Distal Radius and:

a) Ultra Distal DXA; b) Mid Distal DXA; c) Proximal DXA; d) Whole Forearm DXA.

\[
y = 1.3102x + 0.8785, \quad R^2 = 0.4857
\]

\[
y = 0.677x + 0.9684, \quad R^2 = 0.1920
\]

\[
y = 0.425x + 1.0412, \quad R^2 = 0.0765
\]

\[
y = 0.7997x + 0.925, \quad R^2 = 0.2286
\]
The Correlation Graphs between the ‘Whole Hip’ DXA values and the aluminium equivalent density measures of the distal radius are shown in Figure 8.6.

Figure 8.6: Correlation between the Aluminium Equivalent Values of the Distal Radius and Whole Hip DXA.

The Pearson R Correlation values are provided in Table 8.4.
The DXA Values from the Ultra Distal Region provided the strongest correlation with this cortical measure (see Figure 6.32).

Table 8.4: The Pearson R Correlation Values between the Distal Radial Aluminium Equivalent Measures and Forearm and Hip DXA

<table>
<thead>
<tr>
<th>Pearson R Correlation</th>
<th>Ultra Distal</th>
<th>Mid Distal</th>
<th>Proximal</th>
<th>Whole Forearm</th>
<th>Whole Hip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distal Radial AlEq</td>
<td>.697 (p&lt;0.037)</td>
<td>.438 (p=0.238)</td>
<td>277 (p=0.471)</td>
<td>.478 (p&lt;0.041)</td>
<td>.429 (p&lt;0.041)</td>
</tr>
</tbody>
</table>
8.43 The Effect of Limb Dominance on Correlation between Distal Radial Aluminium Equivalent Values and Hip DXA Values

Of the 23 patients in the wrist fracture cohort, 13 fractured their dominant wrist while 10 fractured their non-dominant wrist.

The mean aluminium equivalent value for the ‘dominant’ cohort (i.e dominant wrists) was 1.16 AlEq/mm² (range 0.96 – 1.54: SD 0.18).

The mean aluminium equivalent value for the ‘non-dominant’ cohort (i.e non-dominant wrists) was 1.25 AlEq/mm² (range 0.97 – 1.56: SD 0.18).

There was no significant difference between these two values (p=0.246)

For the ‘dominant’ cohort, the Pearson R Correlation value for the distal radial aluminium equivalent values versus the ‘Whole Hip’ DXA values was R=0.367 (p=0.218). For the ‘non-dominant’ cohort, the Pearson R Correlation value for the distal radial aluminium equivalent values versus the ‘Whole Hip’ DXA values was R=0.380 (p=0.279)

There was no significant difference between the two correlation values (p=0.976).

8.44 Summary

Despite the limited numbers in the wrist fracture cohort, significant correlations were observed between the aluminium equivalent values of the distal radius and the forearm and hip DXA values. This was likely a reflection of the reduced variation in this technique, compared to that in the hip fracture cohort, with reproducible positioning of the wedge, limited scatter phenomenon, limited magnification effects, more accurate soft tissue calculation and less variation in soft tissue values(Dawson, 2009). The aluminium equivalent values were found to correlate with Hip DXA, this concurs with previous studies that have shown that BMD values of the wrist and hip show moderate to good correlation(Cummings et al., 1993).

Limb dominance was not found to have a significant influence either on the aluminium equivalent values or on the correlation with Hip DXA values. It was not possible to assess the effect of limb dominance on correlation with Forearm DXA values, due to the numbers available; however given results from previous studies, with minimal differences between dominant and non dominant forearm DXA results(Sergi et al., 2009, Taafe et al., 1994), it is likely this had a negligible effect.
8.5 Discussion

The results suggested that the aluminium equivalent density technique was a valuable tool for assessment of BMD of the distal radius, but was of limited value for assessment of BMD of the proximal femur. It was likely that such findings were due to a number of contrasting properties in the two different techniques (Dawson, 2009).

The first contrasting property was the area imaged in each of the radiographs. The area imaged in the hip radiographs was far greater than that in the wrist radiographs. This had a considerable effect on the reproducibility of placement of the step wedge, (Dawson, 2009). The decreased area imaged in the wrist radiographs also allowed for considerable closer placement of the step wedge to the ROI compared to the hip radiographs(Dawson, 2009). Not only did this directly improve the accuracy of the technique but it limited the effect of scatter and magnification on the radiographs improving both the accuracy of the aluminium equivalent assessment and the accuracy of the soft tissue assessment(Dawson, 2009).

Another contrasting property was that the analysis of the step wedge in the hip radiographs was complicated by the presence of a mattress and a trolley base interposed between the X-ray plate and the step wedge(Dawson, 2009). While it could be argued that the mattress and trolley base lay between the X-ray plate and the patient as well, it could not be assumed that the X-ray beams in the two different regions would have been affected in the same manner(Dawson, 2009). This was in part due to the altered nature of travel and direction of the X-ray beams in the two different regions and in part due to the altered thickness of the mattress in the two regions due to the effects of displacement of the mattress by the patient(Dawson, 2009). This process was further confounded by inter-patient variations that occurred in the mattress due to the effects of varying patient body habitus. There were no such considerations in the wrist radiographs, with both the step wedge and the wrist sitting directly on the X-ray plate(Dawson, 2009). This again was likely a key factor for the increased accuracy of the technique in the wrist radiographs(Dawson, 2009).
In an attempt to account for the effect of the Perspex jig not lying between the patient and the X-ray film a series of calibration equations were developed. These equations improved the correlation between the aluminium equivalent measures and the DXA measures. However, despite such calibrations, the correlation between the aluminium equivalent measures and the DXA measures remained poor. Such considerations are not required in the wrist radiographs, as both the step wedge and the wrist sit on the X-ray plate directly (Dawson, 2009). This was considered to contribute to the improved accuracy of the ‘distal radius’ technique (Dawson, 2009).

The last cause for the decreased accuracy in the hip radiographs related to the significantly greater volume of soft tissue imaged in these, compared to the wrist radiographs. Not only did this make it difficult to assess the true dimensions of the soft tissue accurately, but it made it difficult to assess similar identifying landmarks on the AP and Lateral radiographs, which were to correlate the levels between the two X-ray views (Dawson, 2009). Similarly, in order to accommodate for the increased image area required with the greater soft tissue volume of the hip radiographs, compared to the wrist radiographs, the X-ray machine had to be placed further away from the X-ray plate. This increased the distance that the X-ray beams had to travel to both the ROI and to the X-ray plate, increasing the distortion effects of magnification and scatter on the final image (Dawson, 2009). Lastly the increased volume of soft tissue is subject to individual variations in deformation, again increasing variations with this technique (Dawson, 2009). Such factors have a limited effect in the wrist radiographs, and again this contributes to the considerable increased accuracy of the technique in these radiographs (Dawson, 2009).

In both the hip and the wrist cohorts, it was not possible to create exactly uniform conditions, particularly relating the milliampere (mA) and kilovoltage (kV) values for the radiographs, due to constraints and individual modifications required for differing patient types within clinical practice. Previous studies have advocated the importance in keeping such factors constant, particularly with digital radiography (Nomoto et al., 2008, Dawson, 2009, Gu et al., 2006, Kolbeck et al. 1999). However,
as this study was performed in the clinical setting, the current and voltage were not kept completely constant in different patients. Indeed the variation observed for these two values was higher in the hip radiographs compared to the wrist radiographs, and this may have contributed to the improved accuracy seen in the wrist cohort (Dawson, 2009). However, for both cohorts, it was considered that the variation for these two values was within acceptable limits. Similarly, any variation in these values would have influenced imaging of both the step wedge and the injured extremity concordantly, altering the aluminium equivalent measures and the BMD measures to a similar degree (Dawson, 2009). As such, while it would have been favourable to have had exactly uniform conditions for the radiographs, this was difficult to achieve in the clinical setting. As long as the variation of such conditions was within acceptable limits, we considered that this should not prevent use of such a technique in the clinical setting.

8.6 Summary

This study suggested that the aluminium step wedge analysis technique could be used as a reliable measure of BMD analysis on digital radiographs of the wrist. This could provide a useful measure of pre-operative BMD estimation of the distal radius and so allow surgical methods and materials to be adapted accordingly. However, further studies would be required to confirm that such findings correlated with bone ‘cut-out’ strength of fixation materials, in order to validate the use of this technique in clinical practice.

The use of this technique in digital radiographs of the hip to assess BMD of the proximal femur was of limited value due to a number of factors that detract from its accuracy. Further work is required to refine this technique before it could be considered for use in clinical practice.
Part IX

Conclusions
Conclusions

In Part IX, conclusions from the results and discussions in the previous sections are drawn pertaining to the hypothesis of this thesis that pre-operative assessment of BMD can be made from digital X-ray images. These conclusions are grouped according to the research questions posed about the three main aspects of the thesis: use of cortical measures, use of trabecular patterns and use of aluminium equivalent grading.

9.1 Use of the Cortical Measures

In this section, the results were used to form conclusions about the values of cortical measures from pre-operative digital radiographs of the hip and the wrist to estimate BMD.

9.11 The Hip Radiographs.

Single values for cortical measures showed variable correlations with DXA. The single measures with the strongest correlation to DXA were the Medial Femoral Cortex one and a half femoral diameters beneath the lesser trochanter and the Lateral Femoral Cortex one femoral head diameter beneath the lesser trochanter. Use of cortical indices failed to provide improved correlations with DXA over single cortical measures. Use of summation of cortical measures provided the strongest correlation with DXA. Intertrochanteric DXA values provided the strongest correlations with the proximal femoral cortical measures, followed by whole hip DXA values. The effect of rotation of the proximal femur on variation of the cortical measures of the proximal femur was within acceptable limits.
9.12 The Wrist Radiographs.

Single values for cortical measures showed variable correlations with DXA. The single measures with the strongest correlation to DXA were the Ulnar and Radial Cortices of the Ulnar Diaphysis.
Use of cortical indices failed to provide improved correlations with DXA over single cortical measures.
Use of summation of cortical measures provided failed to provide improved correlations with DXA over single cortical measures.
No one wrist DXA value provided the strongest correlations with cortical measures.
Wrist DXA values provided marginally improved correlations with the cortical measures compared to Hip DXA values.

9.2 Use of the Trabecular Patterns

In this section, the results are used to form conclusions about the values of trabecular patterns from pre-operative digital radiographs of the hip to estimate BMD.

9.21 Use of the Digital Enhancement Tools to Improve Singh Index Assessment

Use of the digital image enhancement tools on the Image J system to define further the Singh Index on the ‘non processed’ Digital Radiographs from the FUJI System resulted in an improved correlation with the Hip DXA results.
Use of the digital image enhancement tools on the PACS system to define further the Singh Index on the ‘processed’ Digital Radiographs from the PACS system failed to provide an improvement in the correlation with the Hip DXA results.
Use of the inversion tools on the Image J system and the PACS system to define further the Singh Index failed to provide an improvement in the correlation with the Hip DXA results
9.22 The Correlation of the Singh Index with Hip DXA

The Singh Index of the Hip Radiographs provided poor correlation with Hip DXA values.
Correlations were equally poor between the ‘Original’ PACS and the ‘Original’ FUJI radiographs.
Correlations were improved by ‘contrast-enhancement’ of the FUJI radiographs on the Image J system but not by ‘contrast-enhancement’ of the PACS radiographs on the PACS system.
Correlations between the Singh Index and the Hip DXA values were strongest with the Intertrochanteric DXA values.

9.3 Use of the Aluminium Equivalent Grading

In this section, the results are used to form conclusions about the value of the aluminium equivalent grading from pre-operative digital radiographs of the hip and the wrist to estimate BMD.

9.31 The Hip Radiographs.
The ‘Non Perspex-Corrected’ Aluminium Equivalent Grading of the proximal femur showed poor correlations with the Hip DXA values.
The ‘Perspex-Corrected’ Aluminium Equivalent Grading of the proximal femur showed improved correlation with the Hip DXA values but the correlation still remained poor.
The Intertrochanteric DXA values showed the strongest correlations with the Aluminium Equivalent Values.
9.32 The Wrist Radiographs.
The Aluminium Equivalent Grading of the distal radius showed good correlations with the Forearm DXA values.
The Ultra-Distal DXA values showed the strongest correlations with the Aluminium Equivalent Values.
The Aluminium Equivalent Grading of the distal radius showed moderate correlations with the Hip DXA values.

9.4 Clinical Application

Estimation of BMD from digital radiographs of the hip can be performed most accurately using a summation of cortical measures from the proximal femoral diaphysis.
Estimation of BMD from digital radiographs of the wrist can be performed most accurately using an aluminium equivalent grading of the distal radius.
Part X

Recommendations for Further Work
Recommendations for Further Work

In Part X, recommendations are made for further work for each section of the thesis, on the basis of the conclusions.

10.1 Use of the Cortical Measures

10.11 The Hip Radiographs.
While a sufficient number of patients were included in this analysis, repetition of this part of the study with a larger cohort of patients would provide a more statistically robust set of results.
While the aluminium step wedge was used as a calibration device to calculate ‘real term’ measures in this study, such an object is not normally included in clinical practice. A method for calculating ‘real term’ measures on digital radiographs of the hip in clinical practice would aid introduction of this technique into clinical practice.
The results, presented here, found good correlation between the cortical measures and the DXA results of BMD. However the DXA results only provide a proxy measure of bone quality and subsequent fixation strength. Cadaveric studies comparing various cortical measures of the proximal femur with pull-out force required to displace and remove surgical fixation materials from the proximal femur would provide clear information on the value of such measures to direct surgical decision making.

10.12 The Wrist Radiographs.
Due to the consent process required for this section of the study, a limited number of patients were included in this analysis. As such repetition of this part of the study with a larger cohort of patients would provide a more reliable set of results.
While the aluminium step wedge was used a corroboration device to calculate ‘real term’ measures in this study, such an object is not normally included in clinical
practice. A method for calculating ‘real term’ measures on digital radiographs of the wrist in clinical practice would aid introduction of this technique into clinical practice.

Various cortical measures are present on the wrist radiographs. While three specific regions were chosen for this thesis, investigation of other regions may find stronger correlations with the DXA results.

The results assessed the correlation between the cortical measures and the DXA results of BMD. However the DXA results only provide a proxy measure of bone quality and subsequent fixation strength. Cadaveric studies comparing various cortical measures around the wrist with pull-out force required to displace and remove surgical fixation materials from the distal radius would provide clear information on the values of such measures to direct surgical decision making.

10.2 Use of the Trabecular Patterns

While a sufficient number of patients were included in these analyses, repetition of this part of the study with a larger cohort of patients would provide a more statistically robust set of results.

The analyses in this section were performed by the first author. Repetition of these analyses by a number of clinicians would allow for inter-observer reliability of the techniques to be calculated.

Our results assessed the correlation between the trabecular patterns and the DXA results of BMD. However the DXA results only provide a proxy measure of bone quality and subsequent fixation strength. Cadaveric Studies comparing trabecular patterns with the pull-out force required to displace and remove surgical fixation materials in the proximal femur would provide clear information on the value of such patterns to direct surgical decision making.
10.3 Use of the Aluminium Equivalent Grading

10.31 The Hip Radiographs.
While a sufficient number of patients were included in this analysis, repetition of this part of the study with a larger cohort of patients would provide a more statistically robust set of results.

The technique used for the aluminium equivalent measurements had been previously validated by Dawson (2009). This was modified accordingly to account for additional equipment within the set-up. It was not considered necessary to account for the effects of the mattress and the trolley on the aluminium equivalent values of the hip radiographs, however further assessment and normalisation for this may improve the correlation between the aluminium equivalent values of the proximal femur and the DXA values of the hip.

Similarly, we chose to assess aluminium equivalent measures adjacent to the lesser trochanter, as this allowed estimation of the soft tissue thickness at this region, given the available radiographs. Further imaging to allow estimation of the soft tissue thickness around the femoral head and neck would enable calculation of the aluminium equivalent values for these regions. These may show improved correlations with the DXA values.

The results assessed the correlation between the aluminium equivalent measures and the DXA results of BMD. However the DXA results only provided a proxy measure of bone quality and subsequent fixation strength. Cadaveric studies comparing aluminium equivalent measures with the pull-out force required to displace and remove surgical fixation materials from the proximal femur would provide clear information on the values of such measures to direct surgical decision making.

10.32 The Wrist Radiographs.
Due to the consent process required for this section of the study, a limited number of patients were included in this analysis. As such repetition of this part of the study with a larger cohort of patients would provide a more reliable set of results and further assessment of the aluminium equivalent measures of the radial diaphysis,
ulnar diaphysis and metacarpal diaphysis and the correlations of these with the according DXA readings could be performed.

The results presented here showed a good correlation between the aluminium equivalent measures and the DXA results of BMD. However DXA results only provide a proxy measure of bone quality and subsequent fixation strength. Cadaveric studies comparing aluminium equivalent measures with the pull-out force required to displace and remove surgical fixation materials from the distal radius would provide clearer information on the value of such measures for directing surgical decision making.
Appendix 1: Formal Ethical Approval for the Inclusion of the Aluminium Step Wedge in the Radiographs.

Permission to include the Aluminium step wedge in patient X-rays was sought by Dawson (2009) from the South East Scotland Research Ethics Service. Permission requiring no ethical review was granted. A copy of the agreement is in Figure A.1.

Figure A.1. Permission requiring no ethical review to include the Aluminium step wedge in patient X-rays from the South East Scotland Research Ethics Service (Dawson, 2009).
Appendix 2: Formal Ethical Approval for the extra site of DXA analysis for the Wrist Patients

Ethical approval was sought and received from the South East Scotland Research Ethics Service to allow the Wrist Fracture Patients to undergo an extra site of DXA analysis of the uninjured forearm. A copy of the agreement is in Figure C.1.
NHS sites

The favourable opinion applies to all NHS sites taking part in the study, subject to management permission being obtained from the NHS/wSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

Non-NHS sites

The Committee has not yet been notified of the outcome of any site-specific assessment (SSA) for the non-NHS research site(s) taking part in this study. The favourable opinion does not therefore apply to any non-NHS site at present. We will write to you again as soon as one Research Ethics Committee has notified the outcome of a SSA. In the meantime no study procedures should be initiated at non-NHS sites.

Conditions of the favourable opinion

The favourable opinion is subject to the following conditions being met prior to the start of the study:

Management permission or approval must be obtained from each host organisation prior to the start of the study at the site concerned.

Management permission ("R&D approval") should be sought from all NHS organisations involved in the study in accordance with NHS research governance arrangements.

Guidance on applying for NHS permission for research is available in the Integrated Research Application System or at http://www.rfforum.nhs.uk.

Where a NHS organisation's role in the study is limited to identifying and referring potential participants to research sites ("participant identification centre"), guidance should be sought from the R&D office on the information it requires to give permission for this activity.

For non-NHS sites, site management permission should be obtained in accordance with the procedures of the relevant host organisation.

Sponsors are not required to notify the Committee of approvals from host organisations.

It is the responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

<table>
<thead>
<tr>
<th>Document</th>
<th>Version</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP/Consultant Information Sheets</td>
<td>1.0</td>
<td>20 May 2012</td>
</tr>
</tbody>
</table>
Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

After ethical review

Reporting requirements

The attached document “After ethical review — guidance for researchers” gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Notification of serious breaches of the protocol
- Progress and safety reports
- Notifying the end of the study

The NRES website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

Feedback

You are invited to give your view of the service that you have received from the National Research Ethics Service and the application procedure. If you wish to make your views known please use the feedback form available on the website.

Further information is available at National Research Ethics Service website > After Review

Please quote this number on all correspondence

With the Committee’s best wishes for the success of this project
Yours sincerely

[Signature]

Mr Thomas Russell
Chair

Email: joye.dearie@nhslothian.scot.nhs.uk

Enclosures: List of names and professions of members who were present at the meeting and those who submitted written comments if final opinion was confirmed was given at a meeting.

“After ethical review – guidance for researchers” [SL-AR2]

Copy to: Mrs Marise Bucskoglu
Mrs Karen Maidland, NHS Lothian Academic and Clinical
Central Office for Research and Development
South East Scotland Research Ethics Committee 02
Sub-Committee of the REC meeting 31 May 2012

Committee Members:

<table>
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<tr>
<th>Name</th>
<th>Profession</th>
<th>Present</th>
<th>Notes</th>
</tr>
</thead>
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<tr>
<td>Mr Thomas Russell</td>
<td>Retired Consultant</td>
<td></td>
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<td></td>
<td>Neurosurgeon</td>
<td></td>
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<tr>
<td>Dr B Agrawal</td>
<td>General Practitioner</td>
<td></td>
<td>Yes</td>
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</table>
Figure B.1. Formal ethical approval from the South East Scotland Research Ethics Service to allow the Wrist Fracture Patients to undergo an extra site of DXA analysis of the uninjured forearm.
Appendix 3: The Workings and Results from the Investigation to Assess the Effect of the Perspex Jig on X-ray Attenuation in the Hip Radiographs.

This appendix lists the Workings and Results from the Investigation to Assess the Effect of the Perspex jig on X-ray Attenuation in the Hip Radiographs.

The aluminium equivalent values for the first ten steps of the step wedge in the three radiograph tests with the step wedge on the Perspex jig and the aluminium equivalent values for the individual steps of the step wedge in the three radiograph tests with the step wedge on the mattress are listed in Table C.1. The mean aluminium equivalent values for the first ten steps of the step wedge from the three radiograph tests with the step wedge on the Perspex jig and from the three radiograph tests with the step wedge on the mattress are listed in Table C.2.

Figure C.1 demonstrates the step up and analysis graph from the radiograph tests with the step wedge on the Perspex jig. Figure C.2 demonstrates the step up and analysis graph from the radiograph tests with the step wedge on the mattress.
Table C.1: The aluminium equivalent values for the first ten steps of the step wedge in the three radiograph tests with the step wedge on the Perspex jig and the three radiograph tests with the step wedge on the mattress.

<table>
<thead>
<tr>
<th>Step Value (mm)</th>
<th>Test 1 Perspex</th>
<th>Test 2 Perspex</th>
<th>Test 3 Perspex</th>
<th>Test 1 No Perspex</th>
<th>Test 2 No Perspex</th>
<th>Test 3 No Perspex</th>
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<td>371.9198</td>
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<td>556.3946</td>
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<td>562.0114</td>
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</table>
Table C.2: The mean aluminium equivalent values for the first ten steps of the step wedge from the three radiograph tests with the step wedge on the Perspex jig and from the three radiograph tests with the step wedge on the mattress.

<table>
<thead>
<tr>
<th>Step Value (mm)</th>
<th>Mean Test Perspex</th>
<th>Mean Test No Perspex</th>
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<td>5</td>
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<td>557.1145</td>
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</table>
Figure C.1: The step up and analysis graph from the radiograph tests with the step wedge on the Perspex jig

a) the radiograph set-up.

b) the MatLab Programme analysis graph.
Figure C.2: The step up and analysis graph from the radiograph tests with the step wedge on the mattress.

a) the radiograph set-up.

b) the MatLab Programme analysis graph.
Appendix 4: The Correlation Results between the Un-Calibrated Proximal Femoral Cortical Values and the Hip DXA Values.

This appendix lists the Correlation Results between the Un-Calibrated Proximal Femoral Cortical Values and the Hip DXA Values.

Table D1: The Pearson R Correlation Values between the Proximal Femoral Cortical Measures and the Hip DXA Values

<table>
<thead>
<tr>
<th>Pearson Correlation</th>
<th>Intertrochanteric</th>
<th>Femoral Neck</th>
<th>Trochanteric</th>
<th>Whole Hip</th>
</tr>
</thead>
<tbody>
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<td>Lateral Femoral Cortex 1 Uncorrected for Magnification</td>
<td>.558 (p&lt;0.001)</td>
<td>.427 (p&lt;0.010)</td>
<td>.441 (p&lt;0.013)</td>
<td>.539 (p&lt;0.001)</td>
</tr>
<tr>
<td>Medial Femoral Cortex 1 Uncorrected for Magnification</td>
<td>.535 (p&lt;0.002)</td>
<td>.429 (p&lt;0.009)</td>
<td>.519 (p&lt;0.003)</td>
<td>.491 (p&lt;0.005)</td>
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<tr>
<td>Cortical Index 1 Uncorrected for Magnification</td>
<td>.638 (p&lt;0.001)</td>
<td>.466 (p&lt;0.010)</td>
<td>.537 (p&lt;0.002)</td>
<td>.564 (p&lt;0.001)</td>
</tr>
<tr>
<td>Lateral Femoral Cortex 2 Uncorrected for Magnification</td>
<td>.422 (p&lt;0.011)</td>
<td>.411 (p&lt;0.013)</td>
<td>.442 (p&lt;0.002)</td>
<td>.431 (p&lt;0.009)</td>
</tr>
<tr>
<td>Medial Femoral Cortex 2 Uncorrected for Magnification</td>
<td>.589 (p&lt;0.001)</td>
<td>.481 (p&lt;0.006)</td>
<td>.579 (p&lt;0.001)</td>
<td>.555 (p&lt;0.001)</td>
</tr>
<tr>
<td>Cortical Index 2 Uncorrected for Magnification</td>
<td>.614 (p&lt;0.001)</td>
<td>.467 (p&lt;0.009)</td>
<td>.543 (p&lt;0.002)</td>
<td>.565 (p&lt;0.001)</td>
</tr>
<tr>
<td>Modified Tingart Score Uncorrected for Magnification</td>
<td>.593 (p&lt;0.001)</td>
<td>.568 (p&lt;0.001)</td>
<td>.586 (p&lt;0.001)</td>
<td>.529 (p&lt;0.002)</td>
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