

Trochanteric Hip Fractures

Clinical Outcomes and the Cut-out Complication

Alicja Joanna Bojan

Department of Orthopaedics
Institute of Clinical Sciences at the
Sahlgrenska Academy, University of Gothenburg



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alicja.bojan@vgregion.se

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Cover illustration: Micro-CT of the femoral head with implanted hip screw, with courtesy of Harry van Lenthe, Professor of Biomechanics at the Biomechanics Section, KU Leuven (University of Leuven), Leuven, Belgium

“The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them”

Sir William Bragg

British physicist (1862-1942)

To my family

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ABSTRACT

The established treatment for trochanteric hip fractures is internal fixation, either intramedullary (nail) or extramedullary (plate). Approximately 10% of these patients suffer from mechanical complications, the most frequent one being perforation of the lag screw through the femoral head into the hip joint (cut-out). This condition is painful and disabling, and requires revision surgery. The purpose of this thesis was to gain better understanding of the cut-out complication. The complication rate was evaluated in the retrospective series of 3066 consecutive patients treated with an intramedullary nail in a single centre over a 12 years period. Cut-out was found to be the most frequent complication albeit lower than in previous literature - 1.85% (57 patients) (Studies I and II). Combination of three factors: a comminute fracture, poor fracture reduction and non-optimal implant positioning was associated with an increased cut-out risk. From the range of cut-out patterns, i.e. screw cut-out in a variety of paths through the femoral head, it was observed to be a three-dimensional event. To further analyse the pre-cut-out movements, Radiostereometric Analysis (RSA) method was applied in trochanteric hip fractures treated with intramedullary nails (Studies III and IV). Firstly, an experimental study was undertaken to confirm the applicability of RSA in trochanteric fractures. A SawbonesTM model of a trochanteric fracture was mounted on micrometer screws, and radiographed with different true reference displacements. RSA was shown to have high precision and accuracy in this application as translations and rotations in the fracture-implant model could be detected to within $\pm 0.14\text{mm}$ and $\pm 0.03\text{mm}$ (translations), and $\pm 0.5^\circ$ and $\pm 0.18^\circ$ (rotations). The last study prospectively evaluated the 3D fracture-implant movements with the RSA method in 20 patients with stable trochanteric fractures treated with an intramedullary nail and followed for one year. Fracture-implant motion decreased after 3 months and no cut-out occurred. RSA detected clinically relevant movements: translation of the proximal tip of the lag screw in the femoral head, femoral head and lag screw movements relative to the nail. It is important to recognize the "fracture at risk" and, particularly in these patients, achieve anatomical fracture reduction and optimal implant placement. The migration of the implant in bone measured by RSA could be used as a cut-out predictor and enable evaluation of new treatment methods in small groups of patients.

Key words: trochanteric hip fracture, cut-out, intramedullary fixation, RSA, micromotion

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SAMMANFATTNING PÅ SVENSKA

Den etablerade behandlingen av pertrochantära höftfrakturer är internfixation, antingen med intramedullär spik eller extramedullär platta. Cirka 10% av dessa patienter drabbas av mekaniska komplikationer med implantatet, varav den vanligaste är perforation av glidskruven genom ledhuvud in i själva höftleden (cut-out); ett tillstånd som är smärtsamt och funktionshindrande och som kräver revisionskirurgi.

Syftet med denna avhandling är att erhålla bättre kunskap om cut-out komplikationen. Komplikationsfrekvensen med Gammaspikar mättes i en retrospektiv serie med 3066 konsekutiva patienter, alla opererade med Gammaspik under en 12-årsperiod vid ett enda sjukhus. Cut-out var den vanligaste komplikationen, om än betydligt lägre än i tidigare studier - 1,85% (57 patienter) (Studie I och II). Vi fann att en kombination av tre huvudfaktorer: komminut frakturtyp, dålig frakturpositionering och suboptimal implantatpositionering, gav en ökad risk för cut-out.

Olika cut-out mönster framträdde på röntgenbilderna, dvs. skruven skar ut på olika ställen genom höftledskulan vilket visar att ett sådant frakturhaveri är ett tredimensionellt fenomen. Detta studerades närmare med radiostereometrimetoden (RSA, Studie III och IV) på pertrochantära höftfrakturer som behandlades med intramedullär spik. I en experimentell studie verifierades metodens användbarhet och noggrannhet med en höftfrakturmodell där plastben monterats på mikrometerskruvar som tillät kända, stegvisa rörelser i frakturen (Studie III). Det påvisades att RSA har en hög precision och noggrannhet vid mätningen av translationsrörelser ($\pm 0,14\text{mm}$ och $\pm 0,03\text{mm}$) och rotationsrörelser ($\pm 0,5^\circ$ och $\pm 0,18^\circ$) i detta fraktur-implantat system. I det sista delarbetet följdes de tredimensionella fraktur-implantat rörelserna under ett års tid hos 20 patienter med stabila pertrochantära höftfrakturer, samtliga opererade med Gamma spikar. Dessa rörelser avtog efter 3 månader och ingen av patienterna fick en cut-out komplikation. Med RSA kunde kliniskt relevanta rörelser detekteras; skruvspetstranslationen i höftledskulan, höftledskulans och skruvens rörelser i förhållande till spiken.

Det är viktigt att identifiera "riskfrakturer" och särskilt hos dessa patienter sträva efter anatomisk frakturpositionering och optimal implantatpositionering i benet. De små och tidiga rörelser av implantatet i skelettet som kan mätas med RSA-metoden kan prognosticera cut-out och möjliggör att i små patientgrupper utvärdera nya behandlingsmetoder.

LIST OF PAPERS

This thesis is based on the following studies, referred to in the text by their Roman numerals.

- I. 3066 consecutive Gamma Nails.12 years experience at a single centre.**
A.J. Bojan, C. Beimel, A.Speitling, G. Taglang, C. Ekholm, A. Jönsson,
BMC Musculoskeletal Disorders. 2010;11:133.
- II. Critical factors in cut-out complication after Gamma nail treatment of proximal femoral fractures.**
A.J. Bojan, C. Beimel, G. Taglang, D. Collin, C. Ekholm, A. Jönsson,
BMC Musculoskeletal Disorders. 2013;14:1.
- III. Three-dimensional bone-implant movements in trochanteric hip fractures. Precision and accuracy of radiostereometric analysis in a phantom model.**
A.J. Bojan, C. Bragdon, A. Jönsson, C. Ekholm, J. Kärrholm
Submitted to Journal of Orthopaedic Research, peer reviewed
- IV. Fracture-implant motion during healing of pertrochanteric fractures. An RSA study of 20 patients treated with Gamma nails.**
A.J. Bojan, A. Jönsson, H. Granhed, C. Ekholm, J. Kärrholm
In manuscript

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ABBREVIATIONS

ABMC	Autologous Bone Marrow Stem Cells
AP	Antero-posterior
AO	Arbeitsgemeinschaft für Osteosynthesefragen
ASA	American Association of Anesthesiologists
ASIF	Association for the Study of Internal Fixation
BMD	Bone Mineral Density
CTO	Centre de Traumatologie et de l'Orthopedie, Strasbourg
DXA	Dual-energy X-ray Absorptiometry
Gamma3	Third generation of the Gamma intramedullary locking nail
FDA	Food and Drug Administration
HA	Hydroxyapatite
LGN	Long Gamma Nail
ME	Mean Error of rigid body fitting
PCCP	Percutaneous Compression Plate
PF- LCP	Proximal Femur -Locked Compression Plate
PFNA	Proximal Femoral Nail Antirotation
PMMA	Poly(methyl metacrylate)
QCT	Quantified Computed Tomography
SGN	Standard Gamma Nail
SHS	Sliding Hip Screw
SPMSQ	Short Portable Mental Status Questionnaire
TAD	Tip Apex Distance
TGN	Trochanteric Gamma Nail
RCT	Randomized Controlled Trial
RSA	Radiostereometric Analysis

DEFINITIONS

Accuracy	The closeness of agreement between a test result and an accepted reference value
Bone Mineral Density	Amount of mineral matter per square centimetre of scanned bone area
Cut-through	Central perforation of the cephalic screw along its longitudinal axis towards the acetabulum
Helical axis	A line that is simultaneously the axis of rotation and the line along which translation of a body occurs
Osteopenic	Reduced BMD, T-score between -1.0 and -2.5 standard deviations (World Health Organisation definition)
Osteoporotic	Reduced BMD, T-score below -2.5 standard deviations
Precision	The closeness of agreement between repeated independent test results obtained under stipulated conditions
Singh Index	Descriptive osteoporosis assessment tool grading trabecular bone loss in the proximal femur on radiographs
Tip-Apex-Distance (TAD)	The sum of the distances from the apex of the femoral head to the tip of the lag screw on both antero-posterior (AP) and lateral views after correction for magnification
T-Score	Bone mineral density at the site when compared to the young normal reference mean
Yield strength	Stress at which a material begins to deform plastically
Z-effect	Protrusion of the superior hip pin through the femoral head and migration of the inferior lag screw lateral to the nail in implants with two cephalic screws

1 INTRODUCTION

1.1 Trochanteric hip fractures

Epidemiology

Hip fractures occur in more than 18 000 patients in Sweden ¹²¹ annually and in the European perspective, hip fractures are estimated to have reached 620 000 in the year 2010 ⁴⁵. Trochanteric fractures constitute approximately 40% of all hip fractures and subtrochanteric fractures 5%. These fractures are not prone to non-union or femoral head necrosis as the blood supply of the metaphyseal fracture fragments is in general much better than in cervical fractures. Hip fractures are associated with the most severe morbidity and mortality of all the osteoporotic or age-related fractures. For the majority of these patients, sustaining a hip fracture means the temporary or permanent loss of previous degree of independence and a burden on the socioeconomic system ²¹.

Costs

Treatment and rehabilitation of hip fractures is expensive, costing the Swedish state about 2.3 billion SEK (Swedish crowns), or 200 million euro, each year. On an individual level, Zethraeus et al. ¹⁴⁰ estimated the average cost of a hip fracture over a 1-year period based on data covering 1080 women. They found that the cost increased with advancing age, starting at approximately 142 000 SEK for women 50 years of age and rising to 406 000 SEK for women aged 100 years. The cost of a hip fracture with postoperative complication requiring revision surgery increases three-fold according to Swedish National Board of Health and Welfare ¹²¹. Hip fractures account for more than half of all fracture-related direct medical costs. Among women over 45 years, the number of annual patient days in acute care for hip fracture is higher than, for example, for heart attacks, breast cancer, chronic obstructive pulmonary disease, or diabetes mellitus ¹¹⁵.

Hip fracture incidence

In Europe, the highest age-adjusted hip fracture incidences for women were found in Denmark and Sweden (574 and 539/100 000 respectively) while Spain had the lowest incidence of 228/100 000 ⁵⁰. The age-adjusted incidence of hip fractures in Sweden was 590/100 000 for women and 290/100 000 for men in year 2002 ¹¹⁰. The estimates of increasing incidence of hip fractures during the last five decades have been questioned by reports showing a trend-break in the incidence around the world. Several studies have shown a crude hip fracture incidence increase (50%), but the age-adjusted incidence has remained stable ^{2;} ⁴⁴. These changes were attributed to demographic changes in the general population, i.e. higher proportion of aged people rather than the proposed secular

increase in the age-adjusted prevalence of osteoporosis. Some authors have also noted a reversal of the previously observed secular trend with decreasing or stable incidence in hip fractures in women, but increasing incidence in men^{24, 68, 109}. It has been speculated that this could be due to therapeutic and/or preventive measures in women, increasing proportion of immigrants in the Western countries with a lower genetic risk of osteoporotic fractures, a healthier elderly population or individuals at risk who already have two operated hips, due to previous fractures or osteoarthritis.

In contrast, a recent study by Rosengren and Karlsson¹¹¹ reconfirms the trend towards increased hip fracture incidence. The annual number of hip fractures was estimated to almost double during the first half of the 21st century. Based on the hip fracture data during the period 2002–2012, they predicted that approximately 30 000 hip fractures would occur in Sweden in the year 2050. Use of nation-wide rates for 2002 in the predictive model gave similar results, which correspond to an increase in the number of hip fractures by a factor of 1.9 (1.7 for women and 2.3 for men) compared with 2002. Hence, the “trend-break” studies were probably “merely fluctuation on a much larger, and pessimistic curve”¹⁰⁹.

Fracture classification

In the attempt to anticipate the treatment choice and its prognosis, it is essential to divide the trochanteric fractures into stable and unstable fracture subgroups. The stable fractures have been defined as two-fragment fractures, which can be anatomically reduced. The unstable fractures are three-part fractures, which lack the medial or postero-lateral support or are four-fragment fractures⁴⁶.

Despite the many fracture classification systems proposed and developed through the years, none of them is fully reproducible^{3, 29, 35, 102, 116}. The AO/ASIF classification⁸⁶ is the one most commonly used (Figure 1) and trochanteric fractures are labelled as type 31-A. They are subdivided into groups A1, A2 and A3. The A1 and A2 groups are described as pertrochanteric fractures, with the main fracture line running obliquely from proximal-lateral to distal-medial. The A1 group is a simple 2-part fracture while the A2 group represents a multi-fragment fracture. This latter group is subdivided into the 2.1, 2.2 and 2.3 subgroups, indicating the progression from a simpler fracture with a small lesser trochanter fragment to a highly fragmented pattern involving the lesser and the greater trochanters. In contrast, the A3 group fractures are named intertrochanteric since fracture runs either obliquely from proximal-medial to distal-lateral, or it is transverse. These fractures are also described as reverse oblique and transverse intertrochanteric fractures. The A1 fractures are considered stable and some authors include the A2.1 fracture into this group³⁴.

Trochanteric fractures

31 – A

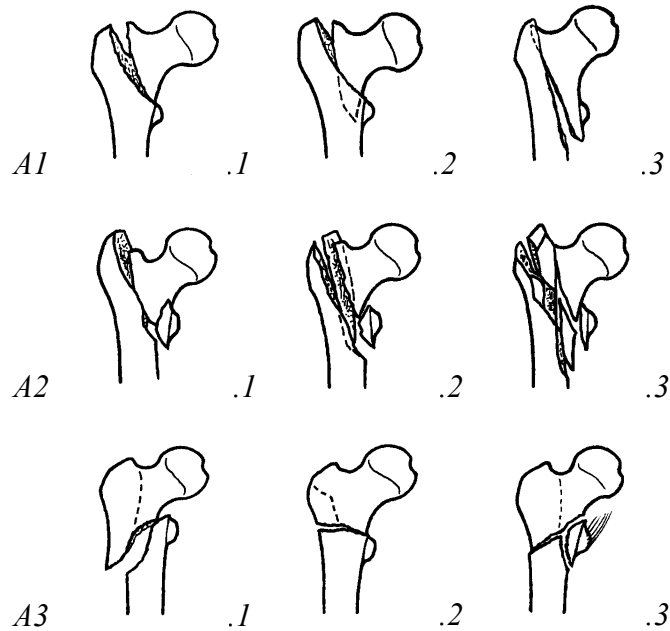


Figure 1. AO/ASIF classification of the trochanteric region ⁸⁶.

Basocervical fractures represent an intermediate form between femoral neck and trochanteric fractures and are defined as proximal femoral fractures through the base of the femoral neck at its junction with the intertrochanteric region (Figure 2) ¹⁴. They are treated in the same way as trochanteric fractures ¹¹⁴.



Figure 2. Basocervical fracture, AO/ASIF 31-B2.1

1.1.1 Treatment of trochanteric hip fractures

Historical background

The treatment of trochanteric fractures was of necessity non-surgical before the introduction of surgical fixation devices, consisting of prolonged bed rest in traction and whole-body cast until the fracture was healed. In old patients, this approach was associated with high complication and mortality rates (more than 40% in the first three months after trauma ²⁶). In addition, fracture healing was generally accompanied by varus deformity and shortening of the leg because of the inability to effectively counteract the deforming muscular forces with traction. The development of modern surgical treatment of hip fractures started in the 1930s with the introduction of the Smith-Petersen nail, which was a three-flanged nail that prevented femoral head rotation in cervical hip fracture fixation ¹²⁰. Sven Johansson, a senior surgeon at the Sahlgrenska Hospital in Gothenburg, was one of the first surgeons to use intraoperative radiographs. In the early 1930s, Johansson cannulated the Smith-Petersen nail, and invented a targeting device for cervical hip fractures. With this, he developed the closed technique by placing the guide pins across the cervical fracture before applying the nail ⁴⁸. In 1937, Thornton ¹²⁷ attached a lateral plate to the Smith-Petersen nail and so the extramedullary implants for the trochanteric fractures came into existence soon followed by others with so called nail-plates (Jewett, McLaughlin). These fixed angle devices, were however mechanically weak and bent or disengaged at the junction especially in unstable comminute fractures as they did not allow impaction. This resulted in a high failure rate and it was soon recognized that a controlled fracture impaction was a precondition for successful trochanteric fracture healing. In the 1950s, the sliding nail-plate was introduced. The Pugh (a sliding trifin nail attached to a one-piece plate with a fixed angle of 135 degrees) and Charnley plates are the precursors of the modern sliding hip screws. The Compression Hip Screw (Richards Medical), patented by Harry Treace in 1956, revolutionized the treatment of hip fractures in the elderly.

Current treatment options

Since the 1950s, the sliding hip screw has become the standard device for fixation of pertrochanteric fractures (AO/ OTA 31.A1–A2) ¹¹⁹ and produces good outcomes ²⁵. It has the advantages of simple instrumentation and surgical technique as well as low cost. Its sliding mechanism allows for controlled impaction and load sharing between the fracture fragments and the implant. However, the unstable and subtrochanteric fractures have always been a challenge for extramedullary devices with frequent complications such as implant breakage, non-union, excessive fracture collapse, and cut-out, of which cut-out is the most common complication with a reported incidence as high as 16.5% in some studies ⁸⁹.

Whilst the development of the intramedullary nailing technique is associated with Professor Gerhard Küntscher who published the technique in 1940s⁵⁹, the modern era of intramedullary treatment of trochanteric hip fractures began with introduction of the Gamma nail (Howmedica GmbH, Kiel, Germany) in the late 1980s. This implant was developed to overcome some of the mechanical complications associated with nail-plates in unstable trochanteric fractures. Later, a large number of different models of intramedullary nails have been developed by other manufacturers, however, the device principles remained the same.

The Gamma nail development started coincidentally in two places in independent and parallel processes. It was developed in Halifax, United Kingdom by Halder and Gill in an attempt to overcome some of the mechanical problems with the Zickel nail^{41, 142} - an intramedullary implant formerly used for the treatment of pathologic subtrochanteric fractures. At the same time, a similar implant for same indications was developed by Grosse, Taglang and Kempf of the Centre de Traumatologie et de l'Orthopedie (CTO) in Strasbourg, France. The first implantations of Mark I Halifax nail were done in 1985; the nail was not cannulated and had no distal locking possibilities. In 1986, the first implantation in Strasbourg was with a 200 mm nail, 19 mm wide proximally and a 2-degree lateral valgus angulation. These two projects were merged and after a number of clinical evaluations and modifications to both implants and instruments, by 1988 one design emerged designated hereafter as "The Standard Gamma Nail". The nail was 200 mm long, 17 mm wide proximally and 11-14 mm distally with valgus angulation of 10°. It was perforated in the proximal segment by a 12 mm cervico-cephalic screw. Two distal locking screws could be fitted for rotational stability of the nail.

1.2 Forces acting on the hip

The key characteristics of the hip joint force components are large magnitudes and frequent variations in direction depending upon the degree and type of locomotion activity. In normal gait, the vertical force component is typically up to 300% of body weight (BW). The anterior-posterior component is prominent and, by each step, alternates between posterior and anterior directions. Reversed torsional loading plays an important role in the mechanical failure of implants. To explain this further, the hip joint forces in a typical patient are shown in Figure 3.

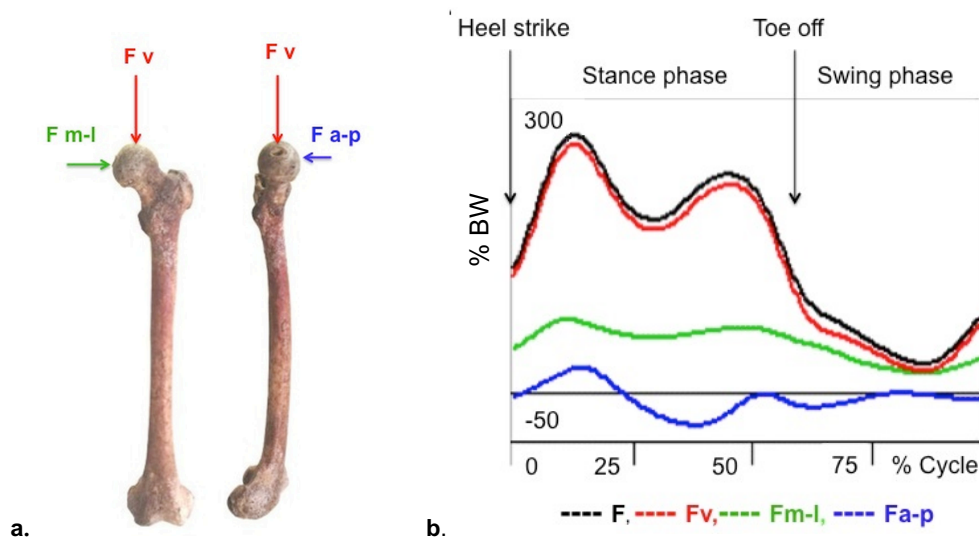


Figure 3. Forces acting on the hip joint during normal walking gait: F_{m-l} =medio-lateral component, F_{a-p} = antero-posterior component, F_v = vertical component from proximal to distal; b. forces presented as percentage of body weight (BW) during gait cycle, F = resultant force; adapted from Bergmann et al. ¹¹.

In Bergmann's studies ^{11, 12}, three components of the resultant hip force were obtained via instrumented hip prostheses implanted in a series of patients. Data for an average patient walking normally show that the main component of force is the vertical one (F_v , Figure 3), reaching typically three times the body weight (BW) with a characteristic two-peak profile, a first peak early in stance (225% BW) and a second occurring late in stance (200% BW). The medio-lateral (m-l) component shows predominantly lateral force throughout stance and is of low level, typically 30-50% of the body weight. In addition, the a-p (antero-posterior) component alternates between posterior and anterior and ranges from -10 to +30% BW. The importance of the torsional component was noted by Wroblewski et al. ¹³⁹ in reviewing failures of the early Charnley "flat back" hip stem where the obliquity of the stem fracture indicated a torsional loading failure. The rotational forces acting on the femoral head fragment with an inserted lag screw can be presumed similar for both extra- and intramedullary implants.

One of the key biomechanical design principles behind the intramedullary nail is a more effective transmission of the hip joint forces via the fracture site to the femoral shaft. The magnitude and the dynamic nature of hip joint forces are one of the main factors that favour an intramedullary device. The side plate of a compression hip screw is at a 30% greater distance from the point of application of the hip joint force and accordingly is subjected to larger bending moments than an intramedullary device (Figure 4). Additionally, the cross-section of the side plate is usually rectangular, which is less well adapted to bear the substantial alternating torsional component of loading compared with the circular section of the intramedullary devices.

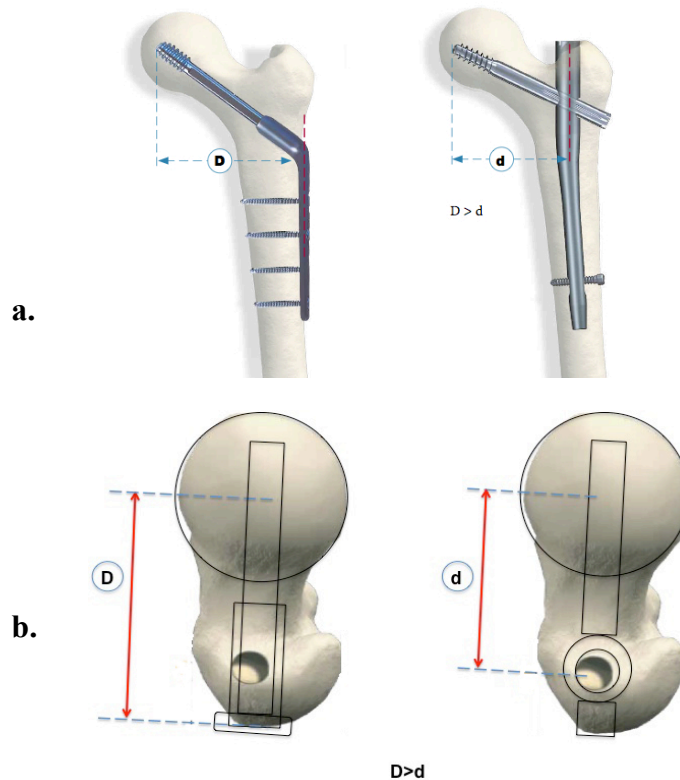


Figure 4. Intramedullary placement of the femoral component of an intramedullary nail shortens lever arm of the hip force, a. AP view, b. axial view

In the treatment of trochanteric fractures, the concept of dynamic osteosynthesis with fracture impaction along the axis of the femoral neck is generally accepted. When it comes to the degree of fracture impaction, intramedullary nail takes an intermediate position between the rigid locked plates for proximal femur and the sliding hip screws. Through its intramedullary position, the nail prevents excessive lateral gliding of the head-neck fragment and moreover, gives a possibility for axial dynamisation through its oval distal locking holes in modern intramedullary nails.

1.3 Early experience with the Gamma nail

Despite the biomechanical advantages, the Gamma nail initially received criticism from orthopaedic surgeons, because of a frequent implant specific complication, i.e. an iatrogenic femoral shaft fracture usually at the tip of the nail⁹². This was believed to be caused by instrumentation problems with distal locking and a non-anatomical implant design²² along with incorrect surgical technique such as using a hammer for the nail introduction^{104, 132}. The 10° valgus angulation in the first generation nail caused mismatch of the medial curvature producing local contacts with stress concentration particularly at the tip of the nail. To overcome these issues, the Trochanteric Gamma Nail was introduced in 1997 with three principal design differences: reduced valgus angulation (4°), only one distal locking screw and a reduced 180 mm length. The

nail diameter was 17 mm proximally and tapered to 11 mm distally (Figure 5). Despite these changes, the device was still considered controversial and it has taken many years to overcome the early prejudice.

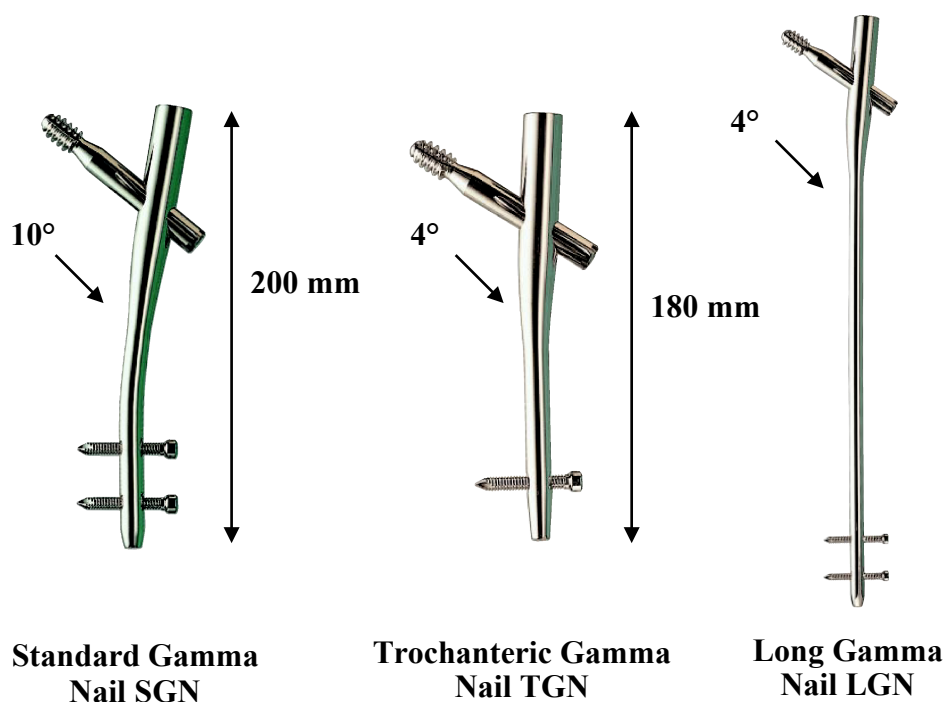


Figure 5. First- and second-generation Gamma nails and long Gamma nail

1.4 Why this work?

At the outset of the present work only a limited number of reports on the Gamma nail were published, the majority of these with low number of patients and from centres with fairly limited experience with the implant^{22, 104}. Gaining access to the database at CTO, it was possible to perform a study of a completely different calibre with an opportunity to review over three thousand consecutive patients treated with Gamma nails spanning a 12-year period from the beginning of its introduction. It is a distinctive series, not only because of its size, but also because it originates from the implant-developing centre where strict adherence to the original operative technique was adopted, and it follows different generations of the implant.

Regardless of the implant used (nails or plates), the cut-out (Figure 6) has been found to be the main postoperative complication. The size of the present series enabled us to study the interrelation of factors contributing to this complication. Analysis of plain radiographs allowed interpretation of three-dimensional movements of the osteosynthesis, though evident limitations of the method did not allow for accurate specification of these movements. These limitations

motivated the author to consider other more specific methods to quantify and study in detail the three-dimensional character of the intramedullary implant motions in trochanteric fractures during fracture healing.

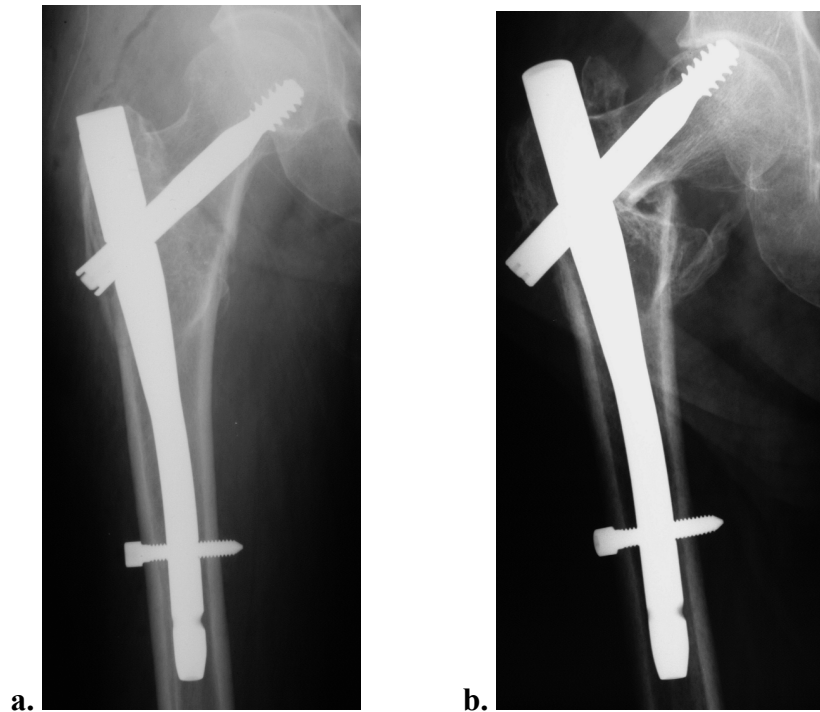


Figure 6. *Cut-out of the lag screw in a trochanteric fracture treated with Standard Gamma Nail; a. Post-operative AP view, b. Varus displacement of the proximal fragment and protrusion of the lag screw into the joint space at three months postoperatively.*

Hence, in the second part of this thesis, the Radiostereometric Analysis (RSA) method was used to allow three-dimensional measurement of the minute movements of the implant-bone systems in a clinical setting. Three-dimensional motions of the osteosynthesis in patients treated with intramedullary nails were visualised with high accuracy and precision that cannot be achieved by any other means available today. In the present study, we have obtained serial RSA measurements at the different time points in the process of fracture healing. Accordingly, migration of the screw in the femoral head could for the first time be traced with high precision and in three-dimensions as well as the motions of the lag screw in the nail itself.

2 AIMS

2.1 Retrospective study - Studies I and II

The aim of the retrospective study was to characterise the spectrum and frequency of complications encountered with the use of the Gamma nail from its introduction and during its later development stages (Study I). Furthermore, this large cohort enabled us specifically to analyse the cut-out complication, its pattern and the contributing factors (Study II).

2.2 RSA study - Studies III and IV

In Study III, a bench test study of the RSA method adapted for trochanteric fracture treated with an intramedullary nail was conducted. The method's feasibility using a phantom construct was evaluated and calculated its precision and accuracy to gain the information about its possibilities and limitations in this particular set-up.

In Study IV, the RSA method was employed in patients with stable trochanteric fractures to assess the three-dimensional motions of the fracture-implant system. The aim was to quantify the expected movements such as lag screw sliding and fracture impaction during fracture healing and to record any adverse motions such as the migration of the lag screw in the femoral head, which can be considered as a predictor for the cut-out complication.

3 PATIENTS AND METHODS

3.1 Retrospective study - Studies I and II

3.1.1 Data collection

Data collection was performed between 1st of March and 30th of June 2003 at Centre de Traumatologie et de l'Orthopedie (CTO), Strasbourg, France. All available documents of patients treated consecutively with Gamma nails were retrieved from hospital archives with the help of archive personnel. Every patient treated with a Gamma nail was registered on a separate list, assuring that no case was missed. Although the Gamma nail system was introduced to the market in 1988, the 1st of January 1990 was chosen as a study starting point, because there were a number of Gamma nail prototypes in the first years. The study end point was set as the 31st of December 2002. The study period corresponded to a 12-year period over which time data was collected for 3066 patients.

All patients with trochanteric, subtrochanteric and combined trochantero-diaphyseal fractures entering the hospital (CTO) were consecutively treated with Standard Gamma Nail (SGN), Trochanteric Gamma Nail (TGN) and Long Gamma Nail (LGN), 110 patients were treated with other Gamma nail designs (Gamma-Ti Nail, Long Gamma-Ti Nail, Dyax Asiatic Nail). No other implants were used for these types of fractures. Since the CTO was a teaching hospital, operations were performed by experienced orthopaedic surgeons, as well as by residents at different training levels.

Data analysis

After reviewing original patient documents in French, data were transferred directly to SPSS forms (English version) stored in a Maxdata Pro 650X notebook, Model 2850. Medical reports were reviewed for epidemiological data such as age, gender, fracture side, aetiology and co-morbidity. Data on anaesthesia, nail type and nail dimensions were recorded. Intra- and postoperative complications were detected with the help of surgical reports, radiographs, and follow-up visit notes.

3.1.2 Radiological assessment

Analogue radiographs were retrieved by archive personnel and evaluated on the radiograph viewer by a single observer - the author. The radiographs of all identified cut-out cases were digitalized with the help of a Fujifilm FinePix S1Pro camera. Parameters such as fracture type, quality of reduction, position of the lag screw in the femoral head were assessed.

Fracture classification

Pre-operative AP and lateral radiographs were used to classify the fractures according to AO/ASIF principles⁸⁶ by one observer. Fractures classified as 31-A1.1 and A1.2 were considered stable.

Fracture reduction

Quality of the fracture reduction was assessed on the immediate post-operative radiographs. For the whole study group fracture reduction was considered unsatisfactory when malalignment of main fragments on the AP radiograph was more than 10 mm, varus/valgus angulation more than 10°, and/or there was more than 20° of angulation on the lateral radiograph. Displacement of the lesser trochanter was not taken into consideration.

In an attempt to assess the influence of the reduction quality on the cut-out event, 82 non-cut-out cases were matched to the 54 cut-out cases according to the following variables: age, fracture classification and gender. For three of the cut-out cases no equivalent patient could be found. A senior, independent radiologist evaluated the quality of reduction separately for five fracture groups: AO/ASIF 31-A1, 31-A2, 31-A3, 31-B2.1 and subtrochanteric fractures. Following reduction criteria were used: the reduction was considered anatomical, when there was a normal alignment (meaning 160° of trabecular alignment in the femoral head³³) on the AP radiograph, less than 20° of angulation on the lateral radiograph, and no more than 4 mm of displacement of main fracture fragments⁸.

Positioning of the lag screw in the femoral head

Lag-screw position in the femoral head was determined from the immediate postoperative AP and lateral radiographs. To assess lag screw position, the placement of the tip of the lag screw in the femoral head was recorded according to an eleven-zones-template of the femoral head (Figure 7).

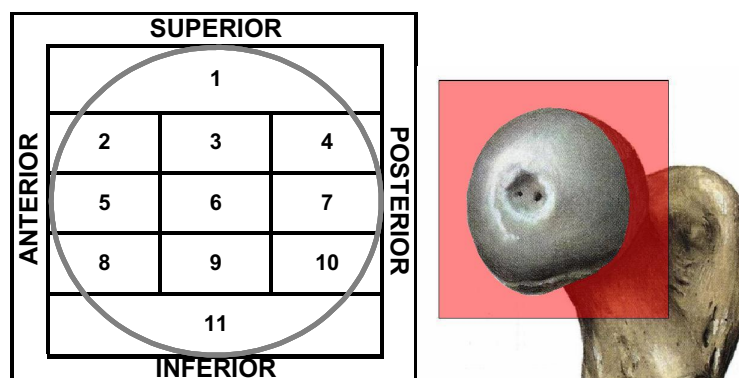


Figure 7. The eleven-zone template of the femoral head; sagittal plane

An additional goal was to assess the position of the lag screw by means of Tip-Apex Distance (TAD) ⁸, which is defined as a sum of the distances from the apex of the femoral head to the tip of the lag screw on both AP and lateral views after correction for magnification. However, it was not possible to collect a valid amount of data, because of inadequate quality of some of the postoperative radiographic records.

3.1.3 Statistical analysis

Results obtained from the retrospective clinical surveillance have been tabulated and statistically analysed by using SPSS packages (version 11.5, SPSS Inc. Chicago, Illinois, USA). The SPSS form was uniquely designed for the study patient population and the questions adapted with help of patient notes samples before starting the study.

Before analysing continuous variables, the data sets were tested for normality by performing the Shapiro-Wilk test. For normally distributed continuous variables, mean values, standard deviations (SD) and 95% confidence intervals (CI) of the mean were shown. For abnormally distributed variables, median, range and interquartile ranges (IQR) were displayed. Mann-Whitney and Chi square tests were used for comparison between groups. Statistical significance for all tests was set at p-values less than 0.05. When appropriate, values were given as percentage, or when the numbers are small, as absolute values.

3.2 RSA studies - Study III and IV

3.2.1 RSA method

Radiostereometric Analysis (RSA) was developed in 1970s by Göran Selvik in Lund, Sweden. Since then, it has been widely applied in arthroplasty research to predict the risk of implant loosening by detecting and quantifying early three-dimensional micromotions of prostheses relative to the bone ⁵². Selvik named his method roentgen stereophotogrammetric analysis (RSA). The term Radiostereometric Analysis, also used to describe this method, has the same abbreviation ⁵⁴. The method has found an increasing number of other orthopedic applications in evaluation of bone growth, joint kinematics and stability, fracture stability, and healing course of spinal fusion, pelvic and tibial osteotomies ⁵⁴. RSA method provides an objective and highly accurate three-dimensional motion analysis of skeletal system in a clinical setting with the help of precise measurements of radiographs and computer-assisted calculation. Small tantalum beads of 0.8 or 1mm in diameter embedded in bone and fixed to the implant are used to create distinct point of measurement enabling calculations of movements between repeated examinations. The position of an implant can also be

determined by shape-matching to three-dimensional models of an implant (model-based RSA¹³⁰). This method may however be difficult to apply to more complex implant geometries such an intramedullary nail (Kärrholm, personal communication). The RSA method has been extensively described⁵¹ and proven to be a safe and accurate method with a precision and accuracy in its completely marker-based versions being at sub-millimetre level in both clinical and experimental arthroplasty and fracture studies²⁰. The principle behind RSA is presented in Figure 8.

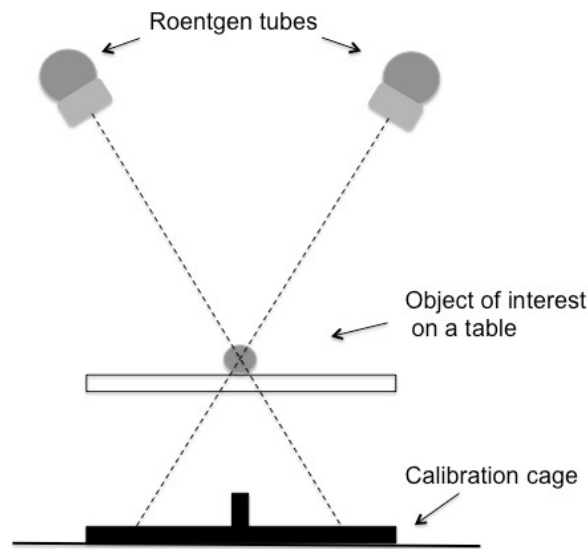


Figure 8. RSA set-up. The calibration cage contains tantalum beads, which define the laboratory coordinate system and is used to compute foci coordinates at each simultaneous exposure of the two roentgen tubes.

Although, the accuracy and precision of RSA is high, it depends on a large number of factors including radiographic equipment, RSA set-up, number of markers and their configurations. Several parameters influence the resolution of RSA. The condition number (CN) describes the distribution of the tantalum markers in a segment. The condition number is a mathematical expression of how the markers in an object of interest, i.e., a “rigid body” or segment, relate to an arbitrary straight line passing through that rigid body¹²². An increasing condition number indicates that the marker configuration approaches that of a straight line. With high CN, the accuracy of the rotational determination about the axis parallel to this straight line will decrease. Determinations of rotational accuracy in directions perpendicular to the line, however, may be very accurate. For this reason, assessment of rotational accuracies about individual axes from the condition number will be misleading by definition¹¹³. Mean error of rigid body fitting (ME) describes the stability of the markers.

Usually, for the RSA method, precision is assessed by test-retest, or double, examinations. In a series of test-retest pairs, variation of the measurements can be determined. The standard deviation (SD) represents a measure of reproducibility and translates into accuracy if the true value is known. If not, it represents the precision of the system. To ensure high accuracy, many tantalum markers should be inserted and scattered as well as possible. High number of markers will reduce the effect of individual measuring errors due to statistical reasons and well-spaced markers will improve the resolution due to geometrical reasons. For determination of prosthetic migration, CNs up to 150 give reliable results¹³⁰. However, for examinations of small joints and bones like cervical spine, higher condition numbers have been used¹¹³. In experimental studies^{72; 91}, the ME of rigid body fitting is reported to be approximately 0.13 mm and mirrors the computation error of the RSA method. Upper level of 0.35 mm is often used in the clinical studies of the hip¹³¹.

All examinations in the present studies were done using an Adora radiographic system (NRT-Nordisk Røntgen Teknik A/S, Hasselager, Denmark) and exposed at 133 kV and 5 mAs, with the use of a uniplanar RSA calibration cage (cage 77, UmRSA Biomedical, Umeå, Sweden). Digital screens (Canon CXDI-50RF, 5.9 pixels, 4096 grayscales, 12-bit) were placed underneath the hip.

3.2.2 Precision and accuracy of RSA - Study III

The phantom

A plastic femur (Sawbones Europe AB, Malmö, Sweden) was cut with a saw to make a model of a trochanteric two-part fracture and then implanted with a Gamma nail (Stryker GmbH, Schönkirchen, Germany). The femoral head and shaft fragments were marked with five and eight 1 mm diameter tantalum beads, respectively. The femoral head fragment was fixed to a separate rotational table and the femoral shaft was mounted on a separate micrometer platform (Figure 9). The platform consisted of an X-Y-Z stage fitted with three spring-loaded micrometers. The intramedullary nail and the lag screw were each marked with four 1 mm diameter tantalum beads by the manufacturer with use of a press fit method (two beads at each end of the two components). The diameter of the tantalum bead was between 1.015 and 1.04 mm and that of the predrilled holes is 0.94 and 0.98 mm. This assured the stability of the beads in the implant. The canal for the lag screw in the femoral head segment was overdrilled by 3.5 mm and beyond the final insertion depth of the lag screw while sliding of the lag screw relative to the nail was blocked. These overdrillings ensured that the lag screw could slide freely along its axis in the head and that the head fragment could be rotated independently of the lag screw.



Figure 9. Phantom model of a trochanteric fracture. The knobs 1, 2, 3 of the micrometer table enable the translations in anatomical coordinate system to proximal, to medial and posterior. The femoral head, attached to a rotational table (arrow), can be rotated backwards and forwards.

Rotation of the coordinate axes

The coordinate axes in an RSA system are aligned with the anatomical body axes as a default setting, where the x-axis coincides with a transverse body axis with the axis directed towards the centre of the body. The y-axis directed cranially corresponds to the longitudinal body axis and z-axis runs horizontally in the sagittal plane, directed towards the observer (Figure 10a). Our model represents the dynamic osteosynthesis of the trochanteric fracture treated with an intramedullary nail. In this construct, the movements along the axis of the lag screw are of importance as they determine the amount of the fracture impaction and lag screw sliding. In order to evaluate the real extent of these motions, the anatomical coordinate axes have been mathematically rotated so that the x-axis coincided with the axis of the lag screw. This has been achieved by determining the coordinates of the proximal and distal ends of the lag screw in the RSA set-up and with use of the distal end of the nail as an origin. The angle measured between the axis of the lag screw and the anatomical x-axis was subsequently used to rotate the coordinate system the amount necessary to align the axis of the lag screw with the anatomical x-axis (Figure 10b).

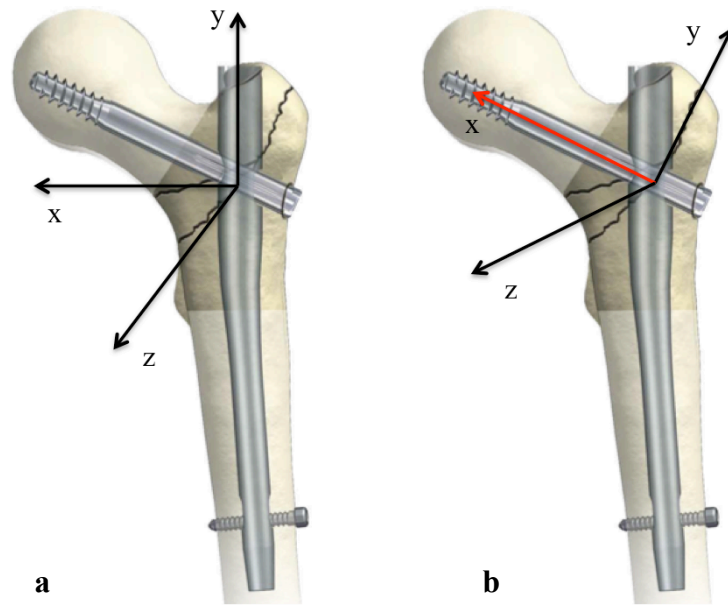


Figure 10. *a: anatomical b: rotated coordinate axes. The transverse axis coincides with the lag screw axis.*

Displacement protocol:

1. Translation of the femoral shaft together with the lag screw along the axis of the lag screw relative to the femoral head, corresponding to x-axis (fracture impaction). The translation was performed in twenty steps of 0.5 mm each resulting in a total motion of 1cm
2. Rotation of the femoral head around the lag screw axis. It was performed in 16 steps of 2° each resulting in final 32° of posterior rotation of the cranial part of the head (mimicking a rotational failure).
3. Three-dimensional fracture fragment translations along the x-y-z axes of the femoral shaft relative to the femoral head. The femoral shaft was moved in steps of 0.5 mm simultaneously in all three planes. From the zero position the femoral shaft was moved 20 steps in order to simulate a total motion of 1cm in each plane and a maximum 3D vector length of 1.732 cm. In the second set-up, the x-, y-, z-translations were performed for each axis separately and sequentially (0.5 mm steps x 20 steps for each plane) resulting in 60 steps.

Displacements 1 and 2 were evaluated in a rotated coordinate system to ensure that the x-axis coincided with the longitudinal axis of the lag screw.

RSA radiographs were exposed at the phantom starting position and thereafter at sequential steps for each type of implant and bone motions studied. All the RSA radiographs (580 examinations) were analysed using the UmRSA Analysis software, version 6.0 (UmRSA Biomedical, Umeå, Sweden).

The condition numbers for the lag screw were 181 and 116 for the nail, and 34 (median, range 33-58) and 30 (median, range 30-43) for the femoral head and

femoral shaft, respectively. The mean error of rigid body fitting (ME) varied from 0 to 0.18 mm for the femoral head and shaft segments and 0.01 to 0.17 mm for the lag screw and the nail.

3.2.3 Clinical RSA study - Study IV

Thirty patients with grossly stable pertrochanteric fractures were treated with tantalum-marked short Gamma nails. The patients underwent their first RSA examination within 24 hours postoperatively, prior to any weight-bearing or sitting-up in bed. After this first assessment, the patients were allowed unrestricted full weight-bearing. The subsequent four follow-up RSA examinations were scheduled at 1 week, 3, 6 and 12 months post-operatively. In all, 20 patients could be followed according to the study protocol. Sixteen patients were female, the median age was 82 years (range: 65-87), the median ASA score was 2 (range 1-3). Nine of the fractures occurred on the right side. The mental status of the patients was evaluated with the Pfeiffer score and had to be higher than 3 for inclusion (median value 10, range 3-10).

Surgical procedure

All patients signed an informed consent prior to the surgical procedure. All operations were performed under spinal anaesthesia by one of five orthopaedic surgeons trained in marking the fracture fragments with tantalum beads. The operative procedures were performed on a traction table, guided with the use of the image intensifier. After fracture reduction and insertion of the intramedullary nail, lag screw guide wire was placed in femoral head aiming for the central-central position as seen on both the AP and lateral views. Once the lag screw canal was drilled, all the instruments and the nail were removed from femur while ensuring that fracture reduction was not lost. Using a specially designed insertion device (UmRSA Biomedical, Umeå, Sweden), six to nine tantalum beads, 1 mm in diameter, were inserted into the trabecular bone of the femoral head through the prepared lag screw canal. In eight patients, three to six beads were placed in the femoral shaft, lateral to the fracture line, through an opening in the lateral cortex and through an opening at the top of the greater trochanter. The nail was then reinserted and the lag screw placed in the femoral head within 1 cm of the subchondral bone, the set-screw was inserted and the nail distally locked.

In this study, the accepted median CN for markers in the femoral head was 50 (range 29-84, n=20) and for the femoral shaft 78 (range 44-151, n=8). The corresponding CNs for the intramedullary nail (n=19) and lag screw (n=20) were 116 (range 115-120) and 182 (range 176-209), respectively. In patient number 4 one bead in the distal tip of the nail was not visible and the CN increased to 221, thus, this patient was excluded from the evaluations of movements involving the nail.

Evaluated movements:

1. Translations of the proximal tip of the lag screw in the femoral head. They were analysed as average translations of the two tantalum markers placed in the proximal tip of the lag screw (point motion). The analysis was made along the anatomical axes.
2. Translations of the lag screw in the nail along the anatomical axes of the body. Additional calculations of translation were made along the transverse axis in the rotated coordinate system (Figure 10b). Moreover, all rotations were measured in the anatomical and the rotated coordinate system in order to present the effect of the coordinates rotation on the measured motions. Motions were measured at the gravitational centre of the figure created by the four markers in the screw relative to the four markers in the nail (segment motion).
3. Translations and rotations of the femoral head relative to the Gamma nail along the anatomical axes as segment motions and an additional measurement along/around the rotated transverse axis (x-axis) (Figure 10b).
4. Translations and rotations of the intramedullary nail in the femoral shaft as segment motion (data available for 8 patients).

3.2.4 Statistical analysis

The precision of the measurements was calculated as 95% and 99% confidence intervals for the phantom study and for the clinical study, respectively, using the standard deviation of the error measured between 2 examinations: $n \cdot SD$, where n is the constant obtained from the T-table adjusted for the number of observations and SD is the standard deviation calculated from 0 with the assumption that there was no systemic bias.

The accuracy was determined using an analysis of variance, by taking into account the variance with each examination and the variance between all five examinations using the formula:

$$a = \pm(x) \sqrt{\frac{\sigma_1^2}{mn} + \frac{\sigma_2^2}{n}}$$

where x = the constant obtained from the T-table adjusted for the number of observations for 95% confidence level with four degrees of freedom, σ_1 = standard deviation of the total average error, σ_2 = standard deviation of the average error of the five examinations ($n=5$), m = number of error observations per examination, n = number of examinations²⁰. Median and range were presented for all motions in the clinical RSA study (Study IV).

3.2.5 Ethics

The institutional review board at the CTO hospital gave ethical approval before the Studies I and II commenced. An approval for conducting Study IV was obtained from the Regional Ethical Review Board in Gothenburg, Sweden.

4 RESULTS

4.1 Retrospective study - Studies I and II

2255 of the 3066 patients were women (73.5%), female:male ratio 2.7. Median age was 81 years, ranging from 14 to 106 years. Stable fractures (AO/ASIF 31-A1) constituted approximately one-third of all fractures and grossly unstable fractures (AO/ASIF 31-A.3) constituted 12.1%. The SGN was implanted in 1623 patients, the TGN in 933 patients and LGN in 473 patients. In 37 patients other nail types were used.

Intraoperative complications

Taken together, 137 (4.5%) complications were observed during operation. Difficulties with distal interlocking resulted in additional perforations of cortices or placement of the distal locking screw outside the nail in 104 patients (3.4%). Thirty-one of these occurred with free-hand distal interlocking in LGNs. Targeted distal nail locking in short nails (SGN and TGN) resulted in 8.6% misdrillings until 1993. With the introduction of a new radiolucent targeting device in 1994, the rate of this complication dropped significantly to 1.1% ($p < 0.001$). Intraoperative fractures were noticed in 17 patients (0.5%) (10 SGNs, 1 TGN and 6 LGNs).

Postoperative complications

Postoperatively and during follow-up 189 complications (6.2%) were detected, amongst which 19 postoperative femoral shaft fractures were observed (0.6%). Thirteen of the 19 occurred with SGN, five with TGN and one with LGN and 15 of these were noted within less than three months postoperatively. Statistically significant fewer complications were seen in the TGN group than in the SGN group. There were 105 patients (6.5%) in the SGN group and 32 patients (3.3%) in the TGN group ($p < 0.001$). Nevertheless, the most common complication was the cut-out of the lag screw independent of the implant design.

The cut-out complication

Fifty-seven cases of cut-out were identified (1.85%). In 45 patients (79%) cut-out occurred within first 12 weeks after surgery (range 8 to 670 days). Twenty-one patients (37%) received no surgical treatment of this complication due to advanced age, major medical co-morbidities and low functional demands. After introduction of the TGN in 1997, the cut-out rate fell from 2.5% to 1.1% ($p = 0.031$). The majority of the lag screws migrated anteriorly-superiorly from its original position and three lag screws migrated posteriorly. Central cut-out (cut-through along the lag screw axis) occurred in eight patients. In six of these the lag screw was prevented from sufficient lateral sliding. In two patients, the lag screw migrated medially relative to the nail.

The cut-out factors

Two fracture types had significantly higher cut-out rate: the complex unstable 31-A3.3 fractures (26.3%) and basocervical 31-B2.1 fractures (26.3%) were overrepresented in the cut-out group ($p < 0.001$). In 44 fractures in the cut-out group, the fracture reduction was not anatomical. There was no statistically significant difference ($p = 0.55$) in reduction quality between the cut-out and the matched group. However, there was a slight overrepresentation of non-anatomically reduced fractures in the basocervical fracture subgroup (31-B2.1) ($p = 0.089$). Screws were most frequently placed in the centre-inferior (910 cases, 34.8%) and centre-centre (792 cases, 30.3%) zone as seen on AP and lateral view. There was a notable increase of the cut-out rate when the lag screw was placed eccentrically in the femoral head. The highest rates of cut-out occurred in the superior-anterior and superior-posterior zones. The cut-out rate for the very inferior zone was remarkably high (4.5%). Patients' age and the neck-shaft angle of the nail had no significant influence on the cut-out incidence.

4.2 Precision and accuracy of RSA - Study III

The RSA measurements of the translations along the lag screw axis showed the precision to be within ± 0.14 mm and the accuracy within ± 0.03 mm. The precision and accuracy for the rotation of the femoral head was within $\pm 0.5^\circ$ and $\pm 0.18^\circ$, respectively. These parameters were smallest when head rotation was assessed relative to the femoral shaft. They were of approximately the same magnitude when measured in relation to the transverse axis (lag screw axis) or as rotation around the helical axis.

For the three-dimensional (3D) translation of the fracture fragments, the precision and accuracy were lower for the x-axis in the 3D translation movement (± 0.286 mm, ± 0.070 mm, respectively), whereas for isolated medial translation of the femoral shaft (x-axis), the precision (± 0.137 mm) and the accuracy (± 0.06 mm) were higher. Analysis of the vector of combined x-y-z translation revealed a precision of ± 0.076 mm and an accuracy of ± 0.028 mm. With increasing condition numbers (70 and 211 for the femoral head and 168 and 310 for the femoral shaft), the reliability of the RSA method for translations was minimally affected, whereas, the precision and accuracy for rotational movements decreased up to fourfold (Appendix 1 in Study III).

4.3 Clinical RSA study - Study IV

In all 20 patients the fractures had healed at 12 months. One patient, in whom the set-screw was not properly engaged in the lag screw, had pain on weight-bearing at six months, but healed eventually.

At the final follow-up the proximal tip of the lag screw had migrated 0.13 mm (range -0.91-3.20 mm), whereas medial/lateral and anterior/posterior displacements were less pronounced.

The lag screw slid laterally (-) in the nail in all 20 fractures (median -5.00, range -19.01 to -1.90 mm at 12 months). In most cases the lag screw had reached this position already at three months. The other movements, including rotation, were much smaller except for the patient with the unlocked lag screw, in whom the screw rotated approximately 26° backwards (counter clockwise, for the right hip) in the nail. The femoral head translated in the inferior, lateral and posterior direction in all fractures. The rotations were small and did not favour any particular direction. No directional tendencies for right or left hips were detected. The nail had subsided 5 mm into the femoral shaft at 12 months in one patient, in whom the nail was distally locked in a dynamic mode. Additionally, approximately 2 mm subsidence occurred in two fractures with the nail locked in a static manner. In these patients, there was a small visible gap between the locking screw and the proximal aspect of the distal locking hole on the postoperative radiographs. Five other nails were properly statically locked and did not move significantly in the distal direction. The other notable movement observed was a tendency of the nail to retrovert (along its axis) in the femoral shaft (median 3.1°, range -1.55 - 6.43° at 12 months).

5 DISCUSSION

5.1 Main findings

This thesis explored a large consecutive clinical series of the Gamma nails. Demography and epidemiology of proximal femoral shaft fractures were analysed in detail. Good performance of the intramedullary nailing technique with low complication rate was demonstrated. The feared implant-specific complication of the femoral shaft fracture at the tip of or under the intramedullary nail was low (0.6%). In spite of the significant decrease in postoperative complications with the 2nd generation Gamma nail (TGN), lag screw cut-out remained the most frequent failure with this implant (1.85%). It was established that the combination of an unstable fracture type, poor reduction and sub-optimal positioning of the implant in the femoral head had the highest risk of the cut-out complication. In the course of radiographic analysis of cut-out cases, different patterns of this event have been observed, which implied its three-dimensional nature. Therefore, in the second part of the thesis, the RSA method was applied to investigate and quantify in further detail the three-dimensional movements in the dynamic construct: the trochanteric fracture treated with an intramedullary nail. As this is the first study of this kind, there were methodological and practical issues to be considered and to confirm that the application of RSA would enable high precision and accuracy in this new application. The RSA method made it possible to detect anticipated fracture motions and lag screw sliding in all studied fractures. The clinically less desirable motions such as migration of the lag screw relative to the femoral head occurred in 13 patients up to 3.2 mm in the cranial direction, even though the fractures were considered as stable.

5.2 Current treatment of trochanteric hip fractures

5.2.1 Nails

The modern era of intramedullary nailing started with the introduction of the Gamma nail with its proposed biomechanical advantages over the sliding hip screw (SHS). A shorter lever arm, not requiring an intact lateral cortex and the medial implant location provided a more efficient load transfer. The shorter lever-arm decreased the effects of the large and dynamic bending moments acting on the implant, thus reducing the risk of mechanical failure through a fatigue process. The alternating torsional loading, due to the medio-lateral hip force component, is better transferred via the intramedullary nail and distal locking screws than by using a side-plate. Additional advantages were suggested to include controlled fracture impaction, a closed reduction with shorter surgical

time and less blood loss, but these latter points were not proven in randomized prospective studies^{39, 96}.

After initial enthusiasm for the new implant, the Gamma nail began to receive mixed reviews in the literature. Particular concerns were reports of intra- and postoperative femoral shaft fractures between 2-8% in the early 1990-series^{7; 18; 41}. Due to this specific complication, its general acceptance was quite slow, particularly in the United States. This has also sparked the development of other intramedullary devices by different manufacturers based on the same principle. Since then, a number of changes have been made to these intramedullary nails to improve their instrumentation and reduce the risk of peri-operative or subsequent fracture around the implant. Recent analyses show that the rate of peri-implant femoral fractures has decreased significantly⁹⁰ (from 2.6 to 1.7%) and that this risk was no longer significant compared with sliding hip screws¹³. This has been accredited to improved adherence to correct surgical technique with intramedullary nails and improvements in implant design.

The low rate of postoperative femoral shaft fractures in Study I was attributed to strict adherence to the proper surgical technique at the original study centre. Regardless of the implant, it appears that there is an increased rate of implant-related femoral shaft fractures after a hip fracture. The hip fracture population is in any case fracture-prone and the consequences of a previous hip fracture such as diminished mental health score, altered hip- and femoral biomechanics, postoperative osteoporosis and increased likelihood of a new fall makes the patient susceptible to new injuries. It can therefore be assumed that there is a "baseline" level of postoperative femoral shaft fractures whatever method has been used to treat the hip fracture. Despite the statistically significant decrease in distal locking problems after the introduction of a new targeting device in 1999, a further decrease in the risk of postoperative femoral shaft fractures could not be shown, indicating that a proper technique was being used from the very beginning. Significantly fewer postoperative complications were seen in the TGN group compared to the SGN group ($p < 0.001$). This probably reflects the effect of a newer design with improved anatomical fit. Apart from these improvements over time, we could not find any proof of a "learning curve" in contrast to other researchers⁶⁰. This may be explained by the CTO being the developing hospital of the Gamma nail, in particular the surgical technique, and has rigorously enforced the surgical principles and technique associated with the use of this implant.

A number of other designs of proximal femoral nails has been introduced by different manufacturers. These include the Intramedullary Hip Screw (IMHS, Smith and Nephew), Proximal Femoral Nail (PFN, Synthes), Proximal Femoral Nail Antirotation (PFNA, Synthes), Trochanteric Fixation Nail (Synthes),

Holland nail (Biomet), Targon PF nail (Aesculap) and ACE trochanteric nail (DePuy/Johnson & Johnson) and this list contains only the larger companies. The PFN was developed and introduced in 1996 by the AO/ASIF group ¹⁶. Two proximal screws were used for fixation of the femoral head and neck fragment. A larger self-tapping 11 mm lag screw was thought to be the load-bearing screw. The smaller, more proximal hip pin was inserted to provide rotational stability and it had no theoretical load-bearing function. It was recommended to be inserted 15-20 mm shorter than the longer lag screw (not exceeding the line between the tip of the femoral neck screw and the top of the IM nail). In practice, this design had two specific failure modes: the so-called “Z-effect” and the “knife-effect”. In the former the screws would migrate both medially and laterally at the same time (hence looking like a “Z” on a radiograph ¹³⁶) and in the latter, the smaller pin would migrate cranially through the femoral head ¹¹⁷. The “knife-effect” could not be confirmed in a clinical study by Schipper et al. ¹¹⁸. In the further-developed model of this construct - the PFNA - a helical blade is inserted by impaction to achieve compaction of the cancellous bone around the implant. This technique is believed to be superior compared with reaming the neck-head fragment. Use of the helically shaped blade instead of a lag screw is believed to result in improved bone-implant interface. The devices with the helical blade controlled rotation and varus collapse better than a single lag screw and demonstrated longer life to cut-out than lag screws in a biomechanical study by Sommers et al. ¹²³ but these proposed advantages could not be shown in clinical trials ¹⁰³.

5.2.2 Plates

The sliding hip screw designs have also been further developed to address the unstable fractures. The Medoff plate uses biaxial dynamisation, allowing for compression along an axis parallel to the femoral shaft in addition to the typical sliding across the fracture and thereby permitting more effective stress transfer through the medial cortex than standard hip screw constructs. Despite this theoretical advantage, Lundsjö et al. ⁶⁹ found no superiority of the Medoff plate relative to the current sliding hip screw constructs.

Trochanteric stabilising plate (TSP) was introduced to support the lateral wall and prevent the fracture from excessive shaft medialisation ⁷⁴. The report showed that there was no significant difference in functional outcome compared with the intramedullary nail treatment for unstable fractures. Despite the ability to retain acceptable fracture reduction, produce satisfactory functional results, and low complication rates, the use of the TSP has not gained any widespread popularity ⁷⁷.

The Gottfried percutaneous compression plate (PCCP, Orthofix) provides a minimally invasive method with a theoretical potential of more rotational stability and a reduction of lateral cortical damage. Although, in the meta-

analysis by Parker et al.⁹⁹ four trials of 396 participants comparing the Gottfried percutaneous compression plate with a SHS found a trend to lower blood loss and transfusion requirements for the PCCP, but no other confirmed differences in outcomes between implants.

The LCP proximal femoral plate (PF-LCP, Synthes) represents a new generation of extramedullary fixation devices for stable and unstable trochanteric and/or subtrochanteric fractures. In the literature, it is referred to as a new implant that allows angular-stable plating for the treatment of complex comminute and osteoporotic fractures⁴³. The manufacturer claims improved proximal femoral fixation in osteopenic bone, achieved by multiple divergent screws locking into the plate. However, the literature reports very high complication rate including implant breakage and loss of reduction, cut-out and non-union^{37, 137, 138} except for a Chinese study showing excellent results with no cut-out complication in 200 patients¹⁴¹. These implants do not allow for fracture impaction, which appears to be the key to a complication-free fracture healing. Analysing Asian studies on hip fracture treatment, one should bear in mind, that the patient population is morphologically different to the European/American one. First of all, the body weight and height are much smaller, which implies different size femora⁸⁷. The implants might also perform better by being exposed to smaller absolute forces acting on the osteosynthesis.

Given this cornucopia of implants, how should the clinician make an informed decision as to which implant is best? So let us have a look at the evidence for and against the devices.

5.2.3 Evidence of performance of plates and nails

When it comes to evaluating the behaviour of new implant designs for hip fractures, the main criterion to be considered is the incidence of fracture healing complications, particularly the cut-out and loss of reduction. Secondary factors are the ease of insertion, degree of surgical trauma, residual pain, functional outcome, implant removal and cost. Often new designs are introduced only with preclinical test data from Sawbones or cadaver bone models and clinical studies emerge much later. An abundance of laboratory and clinical trials have attempted to determine which implant designs exhibit the lowest incidence of cut-out failure. However, the clinical studies have consistently failed to find any significant differences between implant designs¹⁰³ most probably due to the fact that the incidence of implant-related cut-out is masked by the high variability in bone quality, fracture pattern, quality of reduction and implant placement. It may also be that less experienced surgeons, who are learning fracture surgery, contribute to the variability in clinical outcomes.

To date, no consistent differences in cut-out rates have been found between intramedullary nails and sliding hip screws in randomized trials⁹⁷. The Cochrane

review of randomised clinical trials (RCTs) comparing intramedullary nails with extramedullary fixation implants showed that the incidence of cut-out for intramedullary nails was 58/1901 (3.1%) versus 50/ 1902 (2.6%) for the SHS, a difference that is not statistically significant (relative risk 1.15, 95% confidence intervals 0.80-1.66) ⁹⁷. No difference has been found between different nail designs ¹⁰³. A helical blade type of device has been introduced to replace the lag screw and incorporated into the intramedullary device (PFNA, Synthes). There are no clinical studies, which show that the results are any different from traditional nails using a lag screw, and randomized trials with sufficient number of patients are necessary to show what effect this change in implant design might have to reduce the number of complications.

Perhaps, because so many factors interplay in the successful healing of trochanteric hip fracture, the design nuances in the modern sophisticated hardware implants are less relevant as they appear to perform more or less equally. The differences in design features do not necessarily produce measurable differences in the clinical outcomes and may paradoxically lead to entirely new forms of failure unanticipated by the implant designers such as “cut-through” (Gamma nail, PFNA), and “Z-effect” (PFN).

Concerns have been raised in the literature about the increasing popularity of the intramedullary devices without there being clinically convincing evidence in terms of their benefits ⁶. It appears that there is no difference between these implants in terms of complications and outcomes. This has recently been shown by two high quality RCTs comparing nails (Targon and Intertan, respectively) and sliding hip screws ^{78, 98}. Both studies, including stable and unstable trochanteric fractures (AO/ASIF 31 A1, 2, 3), were unable to show any statistically significant differences in terms of complication rate, pain, quality of life or functional outcome.

On the other hand, the question about the clinical value of intramedullary implants in intertrochanteric (AO/ASIF type A3) and subtrochanteric fractures has been recently addressed by the Norwegian hip fracture register study ⁷⁸ showing higher implant-related complication rate in the sliding hip screw group.

In conclusion, the intramedullary nails appear to perform as well as the golden standard - the sliding hip screws in trochanteric hip fractures with a tendency towards somewhat better functional results ⁹⁸. In unstable fractures without the intact lateral wall and in intertrochanteric fractures (31-A3), the intramedullary devices are preferred. Nevertheless, it is the cut-out complication, which still remains an unsolved issue and continues to hamper the clinical outcome when either extra- or intramedullary implants are used. Most recent randomized studies ^{78, 98} show a complication rate between 1.4 and 3.5 % and this number is even higher in a recent retrospective trial (4.2%) ⁵. In the present retrospective

study, the cut-out complication was 1.85%, which is relatively low compared with the literature. While these numbers appear to be rather low, they still represent an important number of patients who suffer, when considering the absolute number of hip fractures treated annually.

5.3 The Cut-out complication

The perception of the cut-out complication has developed from being a two-dimensional event described as the collapse of the neck-shaft angle into varus⁸ to a more general consensus that this complication is the end point of a screw migration and through the cancellous bone - a three-dimensional phenomenon caused by dynamic forces during load-bearing acting on the non-rigid, porous weakened bone¹¹. The multidirectional characteristic was observed by a number of authors in both biomechanical and clinical studies^{15, 31, 70}. However, little is known about the actual three-dimensional movement during healing of trochanteric fractures. Biomechanical studies mimicking physiological (in vivo) loading, have described varus collapse and axial migration of the screw^{19, 123}. However, as with any mechanical experiment, these tests are done under non-physiological conditions and are valid only for the chosen set of parameters. In clinical studies, two-dimensional radiographic measurements of implant migration have been performed to describe implant migration in the femoral head, often only on AP radiographs, underestimating the actual rotational movements^{34; 100; 134}. Based on these limited data, authors drew conclusions about fracture stability, cut-out factors and implants superiority.

Primary and secondary cut-out

Approximately 80% of all cut-out complications occur within first three months³⁰. These early failures are of biomechanical nature influenced by the interplay of the unfavourable combination of osteoporotic bone, complex fracture type, poor fracture reduction and/or implant positioning - “primary cut-out”. These failures should be distinguished from most of the late lag screw perforations, which occur as a consequence of non-unions, infections, revision surgeries or occur as a result of an avascular head necrosis - “secondary” cut-out. In the retrospective analysis (Study II), 72 lag screws that perforated into the hip joint were identified, but only 57 of them were considered to be primary cut-outs.

Cut-through

Central perforation of the cephalic screw along its longitudinal axis towards the acetabulum was a common complication before the introduction of the sliding screw devices in the 1950s. It can also be observed in contemporary intramedullary implants¹²⁵, but it has not been reported for the sliding hip screws to our knowledge. Two mechanisms contribute to this complication pattern. The first one is the failure of the lag screw or a helical blade to slide laterally in the nail. A biomechanical study⁶⁷ showed that the forces required to

initiate sliding were up to three times higher for different nail designs in comparison to the SHS. The ease of sliding of the screw in the barrel of an intramedullary device is determined mechanically by the angle between the screw and the nail as well as by the amount of the screw that is engaged in the barrel of the device⁶². This finding has led to an increased use of larger-angle sliding hip screws. Recently, a concern has been raised about a so-called “cut-through” where the lag screw “actively” migrates medially relative to the intramedullary nail and in extreme cases disengages from the nail and migrates towards and through the acetabulum. The proposed biomechanical explanation for this second mechanism is that in trochanteric fractures without medial support the lag screw can toggle in the nail and can be pushed in through the femoral head towards the acetabulum under cyclic loading (physiological weight-bearing)¹³⁵. In Study II, cut-through (or central cut-out) occurred in eight patients. In six patients the lag screw was prevented from sufficient lateral sliding. In two patients the lag screw itself migrated medially relative to the nail.

5.3.1 Factors that influence the cut-out

The cut-out complication is a multifactorial challenge, affected by patients’ age, gender, grade of osteoporosis, fracture pattern, fracture reduction, implant design, surgical experience and technique. Some of these factors are difficult or impossible to control.

Bone quality

The opinion that poor bone quality increases the mechanical failure rate of an osteosynthesis is widely represented^{32, 64, 65}. However, some researchers have suggested with support of the Singh index or quantitative computed tomography (QCT) that cut-out is not influenced by this factor^{4, 28, 56}. Nevertheless, the patients with the cut-out complication are considered to have osteoporotic bone^{9, 57, 108}. Clinical studies^{4, 8} have shown that increasing age of the patient is predictive for implant failure. On the other hand, the prospective study of Davis et al.²⁸ stated that age did not determine the cut-out rate.

A study of hip densitometry¹⁷ has shown that the centre of the femoral head has the greatest bone density and the trabecular bone architecture is the most homogenous here. The density decreases toward the superior dome of the head. Based on these observations, the author concludes that the implant should be located in the centre of the head to ensure the optimal stability. Implants, which are placed inferiorly, can also be supported by the dense trabeculae of the centre of the head. In the biomechanical study by Brown and Fergusson²³, the mechanical properties of the cancellous bone in the femoral head were determined. The highest yield strength values were observed centrally and inferiorly in the femoral head and the lowest values were found in the intertrochanteric region.

In the retrospective study (Study III), the bone quality was not assessed because of lack of reliable methods, however, the patients with cut-out complication were considered to have osteoporotic bone based on age, gender and the presence of a low-energy fracture.

Fracture type

Relevance of the fracture type, its complexity and correspondingly its stability has been recognized as an important aspect contributing to osteosynthesis failure^{28, 40, 47}. Treatment of two-fragment fractures is usually associated with less risk of complications^{65, 71}. An increased rate of mechanical failures in complex intertrochanteric fractures with subtrochanteric or cervical extension has been repeatedly reported in the literature^{30, 63}. These fractures classified as 31-A3, or intertrochanteric according to AO/ASIF classification, have distinct anatomical characteristics differing from the A1 and A2 fractures. Specifically, there is a fracture line extending through the lateral femoral cortex below the vastus ridge of the greater trochanter. The unique anatomical and mechanical characteristics of the A3 fracture type have been recognized by numerous investigators^{40, 58}. Haidukiewych et al.⁴⁰ reported on high cut-out rate of 12.7% in 47 reverse obliquity fractures (AO/ASIF 31-A3.1 and A3.3) treated with different internal fixation devices. The author also observed inferior results in fractures with poor reduction or poor implant position in the femoral head. In A3 fractures, the fracture impaction does not occur and medial displacement of the femoral shaft with instability of the fracture is common. In a retrospective study, Kyle et al.⁶³ observed four cut-outs in 20 comminute intertrochanteric fractures with cervical extension; all fractures were treated with sliding hip screws. Additionally, the researchers found no significant association between treatment success or failure and Tip-Apex Distance, lag screw position, and adequacy of reduction. Only few reports focus on basocervical fractures as a separate entity^{14, 114}, these demonstrate a high incidence of mechanical complications including cut-out leading to re-operations. In the present study (Study III), the cut-out rate for AO/ASIF 31- A3.3 fracture was 6.5%. The complication rate for basocervical fracture was even higher; i.e. 9%.

Positioning of the cephalic screw in the femoral head

The optimal positioning of the hip screw is still debated in current literature particularly the aspect of central or inferior placement of the screw in the femoral head as seen on the AP view^{75, 85}. There are numerous proponents of either central^{8, 22, 61, 65} or inferior position^{75, 94, 126}. Parker et al.⁹⁴ compared a group of 25 selected trochanteric fractures in which the screw had cut-out with a group of 200 in which the fractures had healed. They noted a significant tendency for posteriorly or superiorly positioned screws to cut-out. They recommended that the screw should be placed centrally or inferiorly on the AP view and centrally on the lateral view. Recently, Guven et al.³⁸ reported an increased cut-out incidence in case of too anterior positioning, whereas De

Bruijn ³⁰ showed that central-inferior and anterior-inferior positions were protective against cut-out. Nevertheless, a peripheral placement, posterior as well as anterior, should be avoided.

The method of the Tip-Apex Distance (TAD) measurement has been widely accepted as an evaluation of the cephalic screw position in the femoral head. Baumgaertner et al. ⁸ described TAD as the sum of distances from the apex of the femoral head to the tip of the lag screw on both AP and lateral views after correction for magnification. Since then, many studies have shown that the increased TAD (>25 mm) correlated to an increased probability of fixation failure ^{5, 10, 30, 36}. The TAD concept supports the recommendation of the central placement of the screw on AP and lateral planes. It was proven to be the only reliable measurement amongst other factors contributing to cut-out ³⁰. The authors conclude that an even lower TAD value of 19.9 mm threshold thus proves to be a better predictor, however, not statistically significant, than the 25 mm threshold.

Navigation technique has enabled to calculate the TAD more accurately in three-dimensions and can be used as an intraoperative tool to achieve a better lag screw placement. Less sophisticated lag screw placement targeting device (One Shot Device, Stryker) has already been introduced and proved to be an effective help in targeting the optimal lag screw placement: 47% of optimal placement without and 87% with the device in a series of 176 patients ¹²⁸.

The present study (Study II) emphasizes the importance of placing the lag screw in the centre of the femoral head on the lateral radiograph. However, it was not possible to define a single optimal zone (inferior, central or even slightly superior) on AP view. These results correlate with the study of Davis et al. ²⁸ where the cut-out rate was not affected by either a superior or an inferior placement as seen on the AP view when the implants were centrally positioned on the lateral radiograph. This finding supports indirectly the concept of TAD: the placement of the lag screw close to the apex of the femoral head on AP view with central placement on the lateral view is essential for the outcome.

Fracture reduction

There is no general system for classifying trochanteric hip fracture reduction. Baumgaertner et al. ⁸ proposed a three-grade classification system. Reduction is considered to be good if the alignment of the femoral head is normal or in slight valgus on the AP view, less than 20° angulated on the lateral view and has less than 4 mm fracture displacement. The reduction is acceptable if either the alignment or displacement criteria are not met and poor if neither of the criteria is met. There are reports ³⁰ showing that poor fracture reduction is associated with a significantly higher risk of screw cut-out compared with good reduction but the scientific proof of this criterion has not been shown to be strong ³⁰.

Valgus reduction is considered to be more beneficial for the outcome than the anatomical one, whereas varus reduction should be avoided as it increases the lever arm of the osteosynthesis, hampering the stability of the construct and hip biomechanics^{5, 93, 95}.

In the retrospective analysis (Study II), no clear difference in fracture reduction could be shown when comparing the cut-out group with the matching controls, which was most probably due to the limited sample size. Nevertheless, a slight overrepresentation of non-anatomical reduction ($p=0.089$) was found in basocervical fracture group with cut-out complication.

In Study II, an unstable and complex fracture pattern, non-anatomical reduction and non-optimal positioning of the lag screw were found to be critical factors contributing to the cut-out complication. All cut-out cases but two had at least one of the mentioned factors. Thirty-one patients were regarded to have an unstable fracture pattern. These were basocervical (AO 31-B2.1) or trochanteric with comminute “pantrochanteric” fracture pattern (AO 31-A3.3). In 44 cases reduction of the fracture was assessed as non-anatomical. The lag screw was malpositioned (outside of the zones 3, 6, 9, Figure 7) in 42 patients. The combination of all three factors or the combination of non-anatomical reduction and non-optimal lag screw positioning was found strongly predictive of a cut-out (Figure 12).

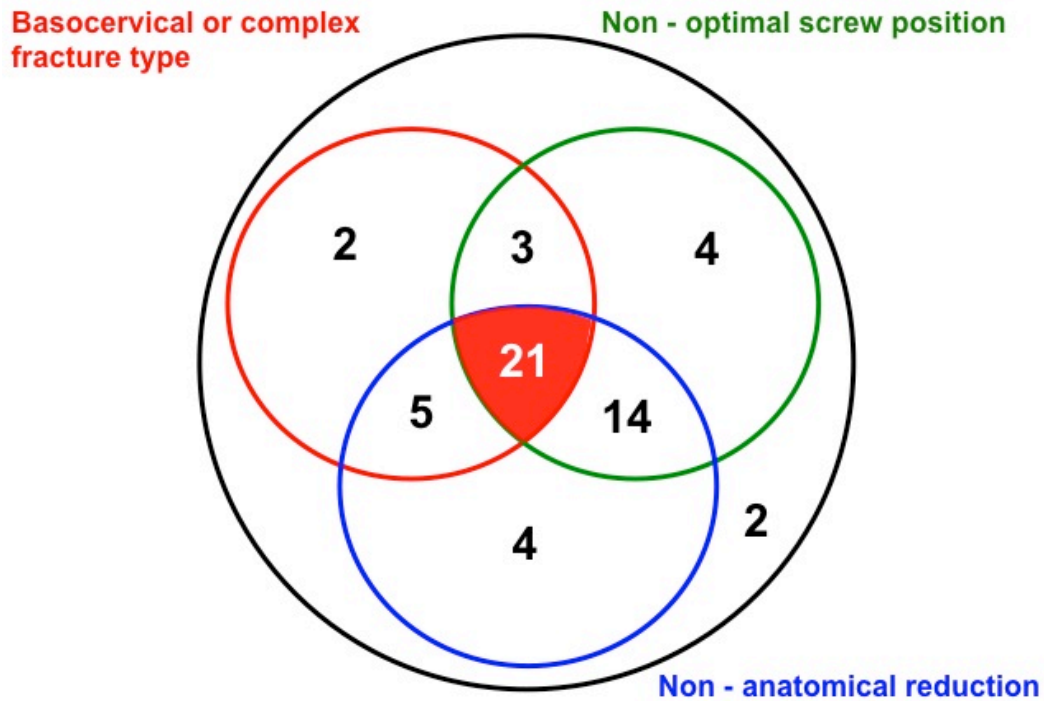


Figure 12. Venn diagram presenting the interrelation of cut-out risk factors, numbers representing the amount of cut-outs, $n=54$

In a number of different reports^{5,36}, the researchers emphasize the importance of TAD as the most important predictor of cut-out regardless of the implant used. TAD may reflect the sum of implant placement per se, fracture reduction and fracture comminution as it is harder to reduce a complex fracture and more difficult to achieve proper implant placement in an unreduced fracture. On the other hand, the limitation of the TAD concept is that it describes only the position of the tip of the lag screw in the femoral head, and in some cases it is possible to achieve an optimal TAD value with poor reduction and inappropriate placement of the lag screw.

5.4 The cut-out countermeasures

The cut-out complication remains an unsolved problem and its absolute numbers will rise as the elderly population increases in numbers¹¹¹. Part of this challenge is due to osteoporosis in these patients, which may make it difficult to achieve a stable fixation with conventional implants. Interestingly, most hardware implants were not developed for the osteoporotic bone and very few of them have an FDA (Food and Drug Administration) approval for use even in osteopenic bone. The paradox of hip fracture devices is that the manufacturers themselves warn that bone disease and inadequate bone quality are the contraindications. Various new methods and devices have been recently developed in an attempt to reduce the rate of this complication. What are the effective methods of diminishing the lag screw cut-out? Can these newer and

different devices, and/or techniques reduce the failure rate? How can it be ensured that such measures have any added clinical value?

Hardware

The improvements of metallic implants target two factors that contribute to the cut-out. These are the instability of the fracture with a rotational component and the quality of the cancellous bone. These include additional antirotation screws (PFN, Synthes or Targon nail, Aesculap), helical blade (PFNA, Synthes), hooks (Twinhook, Swemac), blades (U-Blade, Stryker), and expanding flanges (X-Bolt, X-Bolt Orthopaedics). The helical blade is supposed to increase the contact surface area between the device and the cancellous bone of the femoral head. Since it is inserted without predrilling, it compresses and impacts the adjacent bone and thus, should theoretically minimize the failure risk. Up to date, there is no sufficiently proven advantage to the use of any new hardware implant designs. As mentioned above, the recent meta-analysis by Queally et al.¹⁰³ could not show any clinical advantages of newer nail designs including the additional antirotation screw devices or helical blade device.

Augmentation techniques

As early as in 1975, Harrington⁴² advocated the addition of non-resorbable polymethyl methacrylate (PMMA) cement to the internal fixation construct to reduce the risk of cut-out and fracture collapse. In biomechanical studies of osteoporotic cadaveric specimens with trochanteric fracture models, PMMA supplement around the lag screw threads was shown to decrease the rate of femoral head collapse¹³³. However, the concerns have been raised about the PMMA because of the exothermic reaction with possible heat necrosis of the trabecular bone, disturbances in fracture healing due to interposition of cement and difficulties to remove the cement when a revision surgery is necessary⁶⁶. Nevertheless, Kammerlander et al. asserted that the PMMA augmentation technique is a safe procedure when applied through the perforated helical blade of the PFNA in a series of 62 patients⁴⁹.

Injectable osteoconductive calcium phosphate cements have been evaluated in biomechanical studies¹²⁴ and recently tested in clinical trials^{27, 81} as an adjunct to internal fixation for treating trochanteric fractures. These cements harden without producing the degree of exothermic heat seen with the PMMA materials, develop compressive strength, and are remodelled, although very slowly, in vivo.

Moreover, in the trial by Mattsson et al.⁸¹, calcium phosphate cement has been applied adjacent to the fracture site to improve fracture stability. In this randomized study, the authors evaluated the calcium cement augmentation in 112 patients treated with SHS for unstable trochanteric fractures. There were no postoperative complications in either of groups. The authors reported

significantly less pain at the fracture site at six weeks and a significant improvement in a functional score in the augmented group at six weeks and six months postoperatively. The recent trend is to place the augmentation material around the screw threads to prevent it from excessive migration and eventually from cut-out^{27, 49}.

Interface modification and bioactive implants

Hydroxyapatite (HA) coating has been shown to promote bony ingrowth and provide greater extraction torque than non-coated pins and screws in biomechanical tests. Moroni et al.⁸⁴ reported on 120 patients randomized to either a standard lag screw or HA-coated lag screw. Interestingly, the TAD was >25 mm in 30% of patients in both groups, there were no cut-outs in the HA-coated group and 4/60 (6.7%) in the uncoated group. So far, the use of HA has not gained ground in hip osteosynthesis despite these results.

The idea of adjunct use of autologous bone marrow stem cells concentrate (ABMC) has been tested in the treatment of trochanteric fractures. A recent randomized study of 30 patients showed statistically better functional outcomes, and less pain up to three months (end of follow-up) after surgery when ABMC was added to a hydroxyapatite scaffold around the sliding hip screw at the fracture site¹²⁹. All fractures healed.

The lack of convincing evidence for the clinical benefits of the bone augmentation measures has recently been pointed out in a meta-analysis⁸⁸. The authors demand more stringent research methodology, which is necessary to determine the effect of this treatment.

Accurate well-established methods are available for evaluating the quality of implant fixation in the bone like radiostereometry (RSA), resonance frequency¹ and recently an attempt has been made to use CT-scans to evaluate micro-motions in the trochanteric fractures¹⁰⁷. There are also radiographic studies that quantify the implant-bone system motions in trochanteric fractures, however, two-dimensionally only, for the translation on AP views and their precision has not been evaluated^{34, 101}.

5.5 Radiostereometric analysis in hip fractures

Although not widely spread, the RSA method has previously been applied in hip fracture research and used to measure fracture stability. In the early 1990, Ragnarsson and Kärrholm^{105, 106} studied cervical hip fracture stability treated with hook-pins during healing period. In the first study, the authors emphasise the importance of muscle forces acting on the osteosynthesis, where the centre of the femoral head moved up to 3.7 mm in displaced fractures before the weight-bearing. This motion constituted about one third of the fracture movement during the first postoperative month¹⁰⁵. They observed the shortening of

displaced fractures between 4-16 mm, which continued in over half of the patients up to 6-9 months. Distal displacement of the femoral head was recorded for both undisplaced and displaced fractures and the posterior femoral head displacement was pronounced (up to 5 mm). The displaced fractures displayed retroversion up to approximately 7° and they rotated backwards or forwards about the transverse axis within 13° ¹⁰⁶.

Subsequently, the RSA method has been applied to evaluate whether augmentation with calcium cement improves stability in the early rehabilitation period in unstable cervical and trochanteric hip fractures^{79, 80}. In these studies, calcium cement augmentation was applied close to the fracture site to enhance its stability. The authors showed in both studies that calcium cement application did in fact increase fracture stability by significantly reducing the interfragmentary fracture motions in groups of 40 and 21 patients, respectively. However, it was shown that the augmented cervical hip fracture group had a tendency towards more reoperations⁸². In accordance with the cervical hip fractures studies by Ragnarsson and Kärrholm^{105, 106}, rather small rotational movements of the femoral head around the longitudinal and transversal axes for the trochanteric fractures have been recorded for augmented as well as non-augmented ones⁸⁰.

In the trochanteric fracture study⁸⁰, the authors reported on a precision for fracture fragment movements of 0.16 mm for translations along the transverse axis, and 0.64 and 0.27 mm for longitudinal and sagittal translations, respectively. The precision for femoral head rotations relative to the femoral shaft was 0.91, 1.32 and 0.81° for forward/backward (x), ante-/retroversion (y) and varus/valgus (z), respectively. In evaluation of hip arthroplasty, the corresponding precision has been shown to vary between 0.15 and 0.6 mm for translations and between 0.3 and 2° for measurements of rotation⁵³.

It has been recommended to perform phantom studies to validate the precision of measurements for the studies using high condition numbers^{73, 131}. The present phantom study (Study III) was performed to assess feasibility of the RSA method in the employed model - trochanteric fracture treated with an intramedullary nail marked with tantalum beads. It demonstrated high precision and accuracy. However, the rotational movements of the implant parts relative to each other and the fracture fragments had slightly lower reliability, limited by the shape of the construct and thus, not allowing for better distribution of the tantalum markers. This limitation was also mirrored in the clinical part of the investigation (Study IV), where precision level for the rotations was between 0.50 and 3.31° . Our precision results are not entirely comparable with those of Mattsson and Larsson⁸⁰ due to different study set-up and the fact that we did not assess the fracture movements per se as marking the femoral shaft with tantalum beads was not satisfactory in most of the patients. However, motions of the

femoral head towards the nail (as a surrogate for the femoral shaft) might be compared. The best precision was reached for translation of the head along the lag screw axis (0.2 mm) and for the varus/valgus rotation (0.50°). Nevertheless, the precision for the tip of the lag screw translation in the femoral head was 0.13 mm along the transverse axis and 0.12 mm and 0.32 mm for the longitudinal and sagittal axes, respectively.

In Study IV, the Radiostereometric Analysis enabled the *in vivo* motions of the intramedullary nail in grossly stable trochanteric fractures to be quantified with high precision and accuracy. Characteristic motions of the fracture-implant system, which are clinically relevant to the research question, were detected. For example, cranial migration of the tip of the lag screw dominated over the other two translation components in the femoral head. In all fractures the lag screw slid laterally in the nail and this was mirrored, as expected, by the motions of the femoral head moving both laterally and inferiorly towards the intramedullary nail. Rotations were small and did not favour any particular direction. Interestingly, all femoral heads translated posteriorly relative to the nail and there was a tendency for the nail to retrovert in the femoral shaft. This, most likely, reflects the biomechanics of the hip joint forces, which show that there are large internal moments generated, even in walking¹¹ that would tend to force the head into a posterior direction. This finding is also in accordance with previous observations^{80, 105, 106}.

The small migrations of the implants might be used as a predictive outcome measure for an eventual cut-out event, in the same way as implant migration is used in joint replacement research to predict loosening^{83, 112}. New implants intended to reduce the likelihood of their migration can be evaluated in small study groups with high measurement precision. The present study cannot address the question of patient numbers necessary to detect clinically important differences. However, based on the data scatter, using the unpaired t-test with power set at 80% and statistical significance at $p < 0.05$, 18 patients would be needed in each group to detect a difference of 1 mm of total translation of the tip of the lag screw in the femoral head. This calculation emphasizes the advantage of the RSA requiring small patient groups. Nevertheless, patients lost to follow-up have to be accounted for in this usually frail patient group. In the present study the loss to follow up was 30% and this figure might become even higher in some patient groups.

We were not able to describe a cut-out model for trochanteric fractures, but could nonetheless demonstrate the movement pattern of the osteosynthesis allowed by the dynamic behaviour of the implant and the adverse migration of the lag screw in the cancellous bone. In the future, different patient population with unstable fractures should be studied with this method to describe typical movements that result in the cut-out complication.

6 RELEVANCE OF THIS WORK

Over the last 70 years of surgically treating trochanteric hip fractures there have been many improvements resulting in better clinical outcomes and lower and lower complication rates. One of the early revolutionary steps was the introduction of a sliding mechanism of hip screws in the 1950s and another was the development of an intramedullary nail for unstable fractures in the late 1980s. Since then, the nail design has been gradually improved and implant-specific complications have decreased with an overall improvement in patient outcomes.

Many different “improved” versions of both extra- and intramedullary devices were intended to reduce the most common mechanical complication – the cut-out. For example, there are two screws instead of one, helical blades instead of screws, dynamic side plates instead of static and so on. A plethora of biomechanical and clinical studies at different evidence levels have attempted to prove the theoretical advantages of such new devices, mostly without any conclusive assessment of the likely clinical value. The methods for establishing the usefulness and applicability of any new technology are not standardized, which makes it hard to compare different implant designs. Eventually, the surgeons do their own clinical studies to finally determine the true clinical value, if any.

The general consensus amongst orthopaedic surgeons is that the “fractures at greatest risk” are the unstable ones in the oldest and most fragile patients suffering from osteoporosis (“patients at risk”). The quality of the surgical outcome has been measured by assessing the positioning of the cephalic screw in the femoral head and in more recent times using TAD as a quantifiable predictor of the cut-out complication. Despite the advances in implants and instruments, the strictest adherence to correct operative technique, and an anatomical reduction, we still observe a moderate cut-out rate. Whilst low in frequency the consequences of this event are severe.

In an attempt to address this unsolved problem of cut-out, alternative materials for use together with metallic implants have recently gained ground. Bone augmentation techniques and a variety of implant surface modifications are being introduced to the market/clinical environment. However, there is a lack of clinical evidence for application of these materials and there are demands voiced in the clinical literature for more stringent methods to evaluate the true clinical value of new materials. Orthopaedic trauma research would do well to consider the established models of the arthroplasty field with its systematic scrutiny of evaluation of new implants. The initial step involves exhaustive preclinical implant testing. Thereafter, the first clinical stage consists of prospective

randomized studies that use RSA. The second clinical step involves multicentre studies and the final step is composed of registry studies⁷⁶. The prosthetic orthopaedic community has acknowledged that the fast introduction and widespread use of new implants without this systematic clinical study approach is no longer acceptable⁵⁵. For orthopaedic trauma research, this represents a departure from current practice into new and unfamiliar ground which, if it is to succeed to the level seen in the joint replacement field, must be well-prepared and well-conducted from the technical point of view¹³¹. The first steps toward this have already been taken in Sweden with the creation of the Swedish Fracture Register, and now with the present thesis, the first RSA study of a trauma implant for trochanteric hip fracture. By such standardized evaluation methods, clinical research into novel trauma devices could be much more effective in answering clinically relevant questions, less patients would suffer unnecessary complications and the medical system would be more clinically and cost effective by using only well-established and proven treatment methods.

7 CONCLUSION

7.1 General conclusions

In the present work, we had the possibility to show a good performance of the Gamma nail at its originating hospital. The retrospective study, spanning two generations of these implants captured the significantly lower complication rate with the second-generation device. It seems though that there remains a “baseline” complication rate as it comes to the typical hardware complications such as the femoral shaft fracture at the tip of the implant and the cut-out of the lag screw, of which cut-out is the major failure of this type of osteosynthesis. The RSA method can be successfully used to describe and quantify the three-dimensional movement of the intramedullary implant in the trochanteric fracture with good reliability of the measurements. Even in stable trochanteric fractures, both expected and adverse motions were detectable and quantified. This taken together with the retrospective study means that this thesis is the first comprehensive collection of data describing and linking the patients macro- and micro-biomechanical events that characterize the performance of a specific implant.

7.2 Specific conclusions

- In conflict with previous studies the Gamma nail used to fix trochanteric hip fractures was shown to be a safe method with low complication rate.
- The low rate of femoral shaft fractures could probably be explained by strict adherence to a proper surgical technique.
- The cut-out of the lag screw, as seen with any hip fracture implant remains a major mechanical complication, even with newer nail design.
- 43 out of the 54 patients with cut-out had a combination of two of the three factors that were demonstrated to be risk factors. Only two patients with cut-out did not present with any of these factors.
- To reduce the risk of a cut-out, it is important to achieve both anatomical reduction and optimal lag screw position, particularly with the unstable fracture, as these are the only two factors that can be controlled by the surgeon.
- In a phantom model the relative implant movements and bone-implant movements were detectable with high precision and accuracy to sub-millimetre level, sufficient to enable future research questions to be explored.
- In a prospective clinical study, RSA did measure the combined motions in the dynamic osteosynthesis and was able to discriminate expected fracture compression from adverse migration of the lag screw.

8 FUTURE PERSPECTIVES

It appears that metallic implants have reached a baseline cut-out complication rate, which has not been fully eliminated by the continuous development of these implants. A new group of implant adjuncts such as bone augmentation are about to find their way to the operating theatres with the aim of lowering the rate of mechanical complications. These new cut-out countermeasures do not fit every patient with a hip fracture since we know that maximally 10% of patients will progress to such a complication. Therefore, randomized studies evaluating an average case mix of patients have difficulties to show any significant difference in terms of the complication rate. The sample size calculations reveal that thousands of patients would be needed in such studies. As an example, a difference in reoperation rates of 5% versus 7% would require a total of 4616 patients to detect a significant difference (with 80% power and $p < 0.05$) between intra- and extramedullary devices⁷⁸.

In order to prove the clinical value or otherwise of these new materials, the research should aim at involving the “patients at risk” groups with well-defined risk factors for cut-out. These trials could have fewer and shorter follow-up periods since in the majority of patients this complication occurs within the first three months post-surgery. We should also use methods, such as RSA as it requires small numbers of patients, which is favourable considering the high loss-to-follow-up numbers in hip fracture population. RSA studies could provide more information on the three-dimensional micromotion as a cut-out predictor or serve as mechanical analysis tool for new cut-out countermeasures, revealing different grades of implant migration and perhaps different patterns of this migration.

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