Clinical Evaluation of outcomes in treating Controversial problems in Slipped Capital Femoral Epiphysis using new methods

Thesis submitted for degree of Doctor of Philosophy by published work

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September 2021

Acknowledgement

In my journey to learn, evaluate and reflect on complex problems in hip preservation surgery and its application in Slipped Capital Femoral Epiphysis (SCFE), I pay tribute to my teachers.

As a senior SHO in Alder Hey, Liverpool, in 1996, I got interested in paediatric orthopaedics, and I pay my respect to my teachers there viz. John Dorgan, John Taylor, John Walsh, and James Fernandes.

Prof Wallace Lehman, from NYU, New York helped me to consolidate the foundations in paediatric orthopaedics. Prof Alfred Grant, NYU, New York, laid the first foundation of teaching me complex surgery of Tonnis Triple pelvic osteotomy of the hip. Prof David Feldman (NYU, New York) laid the early foundations of Peri-Acetabular osteotomy (PAO) and limb reconstruction surgery for me. This kindled my interest in hip surgery. (2001-2002).

It so happened that on my return from New York, I became a fellow in Sheffield Children's Hospital, where I learnt a lot under the guidance of James Fernandes, Mike Bell, Mark Flowers, Geraint Davies, and Stanley Jones. However, it was Mr Fernandes who shaped my career and taught me the complex areas of hip surgery and limb reconstruction. I have found Mr Fernandes one of the most talented and versatile surgeons.

Thereafter, I went for a Hip fellowship with pioneer hip surgeon of this generation, Prof Reinhold Ganz. I learnt Surgical Dislocation, PAO, pelvic trauma, and Proximal femoral osteotomy surgery from him in 2004. This was the beginning of my foundations from 2004 to practice as hip preservation surgeon.

In 2006, I travelled to Vail Colorado and learnt hip arthroscopy from the pioneer hip arthroscopist, Marc Phillipon.

I kept learning from the pioneers in hip surgery, and limb reconstruction in my travels. I have worked briefly and observed, Prof Mike Millis (Boston, MA), Prof John Clohisy (St Louis, Missouri), Prof Terry Canale (Memphis TN), Ricky Villar (Cambridge, UK), and Prof Andrea Fontana (Italy).

All these eminent surgeons taught me clinical research methodology alongside surgical skills.

I am indebted to my supervisor Prof Amaka Offiah for guiding me in thesis writing.

I am indebted to James Fernandes for supporting me in complex areas of surgery and to scale up in new challenges of paediatric orthopaedic surgery.

Abstract

SCFE is a challenging condition which can lead to long term problems in the hip.

There are increasing number of complications when severe grade or unstable SCFE is treated with *in situ* pinning. In publication one, I propose a classification which helps in decision making: whether to treat this with percutaneous pinning or open surgery. I allude to the current classifications, and its shortcomings and show that this is a workable classification to assess the magnitude and direction of slip.

In publication two, I describe surgical dislocation approach to correct deformity of SCFE and recreate anatomy of the hip. I evaluate the results and outcomes. I conclude that the AVN risk is similar to other open reduction procedures reported in literature.

In publication three, I describe the avascular necrosis issue with unstable SCFE. I then show how I evolved a technique of salvaging these hips by hinged distraction. I found that distracting the hip, off loads it and prevents collapse and allows the head to consolidate. This technique doesn't work after collapse of the femoral head.

In publication 4, I describe arthroscopic technique of minimising Femoro-Acetabular Impingement (FAI) and treating its ill effects on joint cartilage. I assess the outcome of this surgery and show that early arthroscopy after pinning *in situ* is better, to minimise the damaging effect of impingement on the hip.

In publication 5, I describe the open subcapital neck osteotomy and alignment procedure for severe SCFE and describe its outcomes. I show that surgical dislocation technique is safe and effective in these cases. Our numbers were small, so we perhaps didn't encounter AVN but review of the literature does suggest that this risk can be significant.

In publication 6, I compare the arthroscopic correction of severe SCFE deformity to open subcapital osteotomy in healed SCFE and describe the pros and cons of each treatment and its limitations. Both these cohort of patients were satisfied and none of the arthroscopic group of patients have ever needed a secondary proximal femoral osteotomy. The freedom of movement they gained by intra-articular correction of FAI suggests that this may be a major issue in severe SCFE rather than loss of internal rotation.

Table of Content

Chapters (numbers 1 to 11)

Chapter 1: Introduction

Epidemiology

Incidence of SCFE varies from 1-80 :100,000.[1–4] It is more common in boys with the peak incidence occurring in boys at 12-15 years and girls at 10-13 years. Known risk factors are obesity, hypothyroidism, hypogonadism and family history.[5–7]

SCFE is bilateral in about 20% of the cases; 50% present initially with both hips involved and the other 50% develop it on the other side later. Majority of sequential bilateral slips develop it within 18 months of the first side involvement. Some studies showed a much higher incidence of bilateral hips involvement.[7–9] Jerre et al[8] reported on a series of 100 patients with SCFE after an average follow up of 32 year. He estimated that (59%) had bilateral SCFE. More interestingly in 42 of these 59 patients (71%), slipping of the contralateral hip was asymptomatic. In 23 patients (23%), the diagnosis of bilateral slipping was established at primary admission, in 18 (18%) later during adolescence, and in 18 (18%) not until the patients were reexamined as adults and the primary radiographs were reviewed. Lehmann et al[10] in their population based study showed an incidence of 6.6% in young adults having SCFE morphology.

Pathophysiology

Several anatomical, histological, mechanical factors play roles in the disease process. During pubertal growth spurt the hypertrophic zone of growth plate, under the influence of growth hormones, widens. Forces across the hip are typically directed downwards and backwards. In association with this the teenagers being active in sports transmit huge force across the hip. All this in combination with higher Body Mass Index (BMI) creates an ideal situation for the capital femoral epiphysis to slip in inferior and posterior direction.[5,11,12]The hypertrophic zone normally constitutes 15-30% of the normal growth plate. In SCFE, this increases to up to 80% of the width of the growth plate. Histologically, abnormal cartilage maturation, endochondral ossification, and perichondral ring instability occur. This leads to less organization of the normal cartilaginous columnar architecture which weakens the growth plate. Slippage occurs through this weakened area.[13]

Moreover, some anatomical changes such as retroversion of > 10 ° and the inclination of the growth plate of the proximal femur increase the net effect of shear forces across the growth plate and predispose to slippage. Femoral and acetabular retroversion have been implicated in patients with SCFE.[14–18] Trauma is often implicated by tipping a narrow balance to cause the slippage.

The hormone leptin, which is secreted by adipose cells and primarily provides negative feedback at the hypothalamus to signal satiety, has been shown to cause widening of hypertrophic zone of physis when present in elevated levels in animal models.[19–21] Obesity has been linked to leptin resistance, in which serum leptin levels must exceed the normal levels in non-obese peers to provide adequate satiety feedback, secondarily resulting in greater signalling at other sites of action.[20,22] Leptin receptors have been identified on articular and physeal chondrocytes in animal and human studies.[19,23–25] Animal studies have shown that, through these physeal receptors, leptin stimulates chondrocyte hypertrophy and proliferation, with alterations in leptin levels leading to an elongated physis, disturbed columnar structure, cellular apoptosis, and decreased expression and organization of the type-II and type-X collagen typically found throughout the hypertrophic zone.[19,26–29] Halverson et al[30] demonstrate an association between elevated serum leptin levels and SCFE, regardless of BMI.

Natural History

There has been a worldwide consensus that SCFE should be treated. The type, timing of treatment and postoperative protocol vary in different centres and parts of the world and even within the same centre treatment can vary based on the presentations, resources and personal expertise and preferences. Therefore, it is impossible to establish the natural history of SCFE as almost all published series report on treated SCFE and the volume of subclinical cases is unknown.

Carney and Weinstein[31] published a series of 31 untreated chronic SCFE with a long term follow-up (ranged from 26 to 54 years). There were 17 mild, 11 moderate and 3 severe SCFEs. The mean Iowa Hip Score (IHS) was 89 points (92 points in mild slips, 87 points in moderate slips and 75 points in severe slips). All severe and moderate slips showed radiographic features of osteoarthritis (OA) in contrast to 13% of those with mild slips. Complications occurred in 4 slips (1 AVN and 2 further displacements developed in 3 severe slips and 1 chondrolysis in 1 mild slip).

In another series, Carney et al[32] reported on 155 SUFEs in 124 patients at long-term follow up of 41 years. Forty-two percent of the slips were mild; 32% were moderate; and 26% were severe. Various treatments methods were used. These categorised into pinning in situ or re-alignment procedures. They found that the natural history of the malunited slip is mild deterioration related to the severity of the slip and complications. The Iowa hip score deteriorated significantly over time (P= 0.0025), with more poor results (a rating of ≤ 80 points) with each ten-year increase in follow-up. Realignment procedures were associated with a risk of appreciable complications and adversely affect the natural history of the disease. In the hips that had been realigned, the mean Iowa hip score was ≤ 89 at (40-49 years of follow-up) when the slip had been mild, at (30-39 years) when the slip had been moderate, and at (20-29 years) when the slip had been severe.

Re-alignment procedures and the surgical technique have evolved significantly over the last 40 years, and it would be interesting to see whether the above findings and trend remain the same with our modern surgical techniques.

SCFE and its sequelae have not been a large contributor for total hip replacement. The Nordic joint registry (1995-2006) indicated that paediatric orthopaedic collectively accounted for 3.1% of 69,242 THRs in Denmark, 1.8% of 140,082 THRs in Sweden and 8.6% of 70,138 THRs in Norway.[33] Larson et al[34] reviewed 33,000 hip replacement performed in their centre between 1954 and 2007 and found that SCFE was the indication for replacement in 38 hips (in 33 patients = 0.1%). The main reasons for hip replacement in this subset were AVN or chondrolysis in 25 hips and degenerative changes and/or impingement in 13 hips. All slips in their series underwent either pin fixation or primary osteotomy. They found that the mean time from slip to hip replacement was 7.4 years in patients with AVN or chondrolysis and 23.6 years in patients with degenerative change ($P<0.0002$).

Clinical presentation

Typically, the child presents with complaints of knee, groin, medial thigh, or hip pain associated with a limp. Parents and friends may have noticed that the child's foot points outward. The knee pain which is a referred pain from obturator nerve usually confuses the treating clinician and often delays the diagnosis. Acute slips may have a more dramatic presentation with sudden severe pain and inability to walk.

Limping and out toeing gait may be noted on careful clinical examination. The affected leg looks short and externally rotated when patient is lying on their back. The hip movements may show obligatory external rotation (Drehmann's sign) on flexion of the hip.[13,35] There is reduction in abduction of the hip and patient can have antalgic gait.

Chapter 2: Controversy in SCFE management

There are following controversies in SCFE management that I have tried to address in my clinical studies:

1. Current Classifications and evaluation of a new classification that helps in decision making.

   SCFE has been historically classified as per presentation in form of acute, acute on chronic, and chronic. To this classification there was addition of a pre-slip category.
   Loder (1993) proposed a classification based on presentation of instability which is invaluable in assessment of risk of AVN. Kallio et al (1995) suggested instability by presence of hip effusion. They classified SCFE as acute if there is effusion, chronic if there is remodelling and acute on chronic if there is remodelling and effusion present on ultrasound scan images.
   Southwick (1967) classified it with angular displacement as mild<30^0 moderate 30^0 to 50^0 and severe>50^0. Fish (1994) has classified it as mild<30^0 moderate 31^0 to 60^0 and severe>60^0.
   Wilson (1965) classified this as percentage displacement of femoral head over the neck as mild< $1/3^{rd}$, moderate between $1/3^{rd}$ to ½ and severe >half. Cohen et al (1986) described the epiphyseal angular displacement on CT scan. However, no classification was proposed.
   We evaluated a novel method of oblique plane classification to assess the plane of displacement of the deformity and the true magnitude of the deformity. This was very useful in assessing whether they could be pinned in situ safely or needed some reduction to be pinned in situ. This classification was subsequently evaluated by other experts in subsequent papers and found to be very helpful.

2. Problems about methods of open reduction of SCFE and use a new approach of Surgical Hip Dislocation to anatomically correct the SCFE deformity.

   Several osteotomies to correct the deformity have been described for acute, acute on chronic SCFE and its complications rates of AVN. Fish (1984, 1994) described cuneiform osteotomy technique for correction of SCFE deformity through Watson-Jones approach. Parsch et al (2009) described their technique of partial to complete reduction for acute/? unstable SCFE through Watson-Jones approach. Catterall (2006) and Hashemi-Nejad (2015) described their type of cuneiform osteotomy through Smith-Petersson approach. Dunn and Angel (1978, 1988) described their technique of open reduction through a trochanteric flip type of approach. Ziebarth et al (2009, 2012, 2017) evaluated the Surgical dislocation technique for open reduction of the SCFE. We evaluated our results with this approach in 28 cases of which 17 were unstable in our series and found that AVN rate is similar and at lower end of spectrum for unstable SCFE.

3. Issue about Avascular Necrosis (AVN) of the femoral head in unstable SCFE; controversy of current treatment options and evaluation of a new method to preserve these hips.

   Once AVN happens in SCFE the die is cast for collapse of the femoral head, with pain, stiffness and secondary OA. AVN rates have been described for unstable, acute, and acute on chronic slips in literature by various techniques. We reviewed the literature and described various studies that looked at the true unstable slips, effect of unstable slips with closed or open reduction and timing of open or closed reduction. From these studies it was apparent that closed reduction could be attempted in acute slips within first 24 hours of presentation. After that period an attempt to reduce it closed increases the AVN risk several-fold. It is also recommended that open reduction should be done within first 24 hours, failing which it should be done after minimum of 8 to 14 days to minimise risk of AVN. It also appears from literature that closed reduction attempted in first 24 hours has similar or lower risk of AVN than any method of open reduction.

   However, none of the above approaches has ever salvaged an AVN hip to near normal shape of femoral head without collapse. We describe our study over several years of how we evolved a method of salvaging the hips that have established AVN after fixation either, open or closed.

4. Current treatment in chronic severe SCFE, its problems, and proposal of controversial treatment for healed SCFE.

   Several methods have been described in correcting severe deformity in chronic SCFE. Capital realignment procedures and femoral neck osteotomies have been described, but because of the concern of AVN, Gage et al (1978) proposed basal or extracapsular osteotomies as safe approach to the hip to reduce the risk of AVN. We discuss the merits and risks of various approaches to correct the deformity. It is acknowledged in literature that there is a limit to the correction of the deformity with extracapsular osteotomy.

We evaluated the surgical dislocation of hip approach to correct the SCFE deformity in 18 hips, of which 12 had closed physis. We had no AVN and describe this technique as low risk for AVN. However, I express grave concern for capital realignment procedure being a panacea. The literature has shown varying incidence of AVN from 0-100% and there is therefore concern for this technique or any other technique of capital realignment being reliably reproducible. The literature is of course not very clear on acuteness of the slips because most papers historically have a mixed group of cases. However even recent studies evaluating capital realignment procedure for chronic slips has shown high AVN risk of 29% (Sikora-Klak et al, 2019).

5. Treatment of SCFE impingement with arthroscopy and evaluating its outcome

Here we touch base on the issue of Femoroacetabular impingement (FAI) and its potential of causing significant damage to the joint cartilage. It is well known that arthroscopy can address the FAI issue in mild SCFE. However, we extended our approach to even moderate and severe SCFE controversially. We then evaluated our results. The issue with moderate to severe deformities is that there is considerable deformity in the lower limb originating from the slip in the hip. This cannot be adequately corrected with arthroscopy. We found that Arthroscopy was very powerful in addressing intraarticular issues emanating from cam deformity secondary to SCFE.

6. Controversially extending the indication of arthroscopic correction for moderate to severe SCFE and comparing it with open surgery.

Here we reviewed the literature of arthroscopy and its limitation in correction of SCFE deformity. We found that to address moderate to severe SCFE related impingement one must be very skilled in arthroscopy. We, like many other arthroscopists, have addressed severe SCFE cam deformity adequately to prevent further damage to the chondrolabral junction and acetabular cartilage.

We described various osteotomies to correct deformity and compare our technique of subcapital osteotomy in healed SCFE in 12 cases. We found the correction is excellent and the improvement in hip scores was much larger than the arthroscopy group. However, we found that patients in arthroscopy group had sufficient improvement and were able to do most activities without problem and didn’t ask for any derotation osteotomy. We found that this osteotomy approach can address full extent of deformity and correct FAI. But this approach is surgically demanding, may not be reproducible as per the review of literature which has shown that this method can carry significant risk of AVN.

Chapter 3: Narrative

In 2004, I started my career as Consultant Orthopaedic Surgeon. At that time, there were handful of surgeons practicing hip preservation surgery. SCFE was an area with lot of potential to use such techniques. I had learnt these techniques in New York on my fellowship in 2001-2002. Thereafter, I was a Hip fellow with Prof Ganz in 2004. He taught me surgical dislocation technique for correction of SCFE deformity. In 2006, I travelled to Steadman-Hawkins Clinic in Vail, Colorado to learn the hip arthroscopy technique for correction of hip Impingement from Marc Phillipon. At that time, Reinhold Ganz was the pioneer and originator of Hip Preservation specialty and Marc Phillipon was the pioneer in Hip arthroscopy techniques for hip preservation. I was fortunate to learn from these pioneers and I owe my gratitude to these teachers.

SCFE has been a very difficult area in management in paediatric orthopaedic surgery. There are several aspects of its presentation that have challenged the skill and acumen of paediatric orthopaedic surgeons. Historically following questions have remained in almost all facets of presentation and management of SCFE:

1. Mild to moderate SCFE are pinned in situ but the deformity of metaphyseal bump and Cam FAI is left untreated. Will this deformity not cause degeneration of the joint cartilage? Will this deformity remodel?
2. Stable severe grade SCFE presentation is also of a major concern. There is no established consensus in treating this in one way. Should one do intertrochanteric osteotomy and leave the intraarticular impingement unchecked? Should one do subcapital femoral osteotomy and risk AVN? Should one perform intertrochanteric/ subtrochanteric osteotomy and at the same time do femoral head neck osteoplasty thus creating secondary deformity at the intertrochanteric level with changes in biomechanics in the lower limb?
3. FAI in mild, and moderate SCFE is a concern. Does this always need treating? Should it be treated with open surgery. Can it be treated with minimally invasive surgery like arthroscopy?
4. Severe chronic SCFE needs correcting, but the dilemma remains what is the best technique? Is open surgery safe? Is arthroscopic surgery able to correct the deformity or only the impingement component? What are the limits of arthroscopy?
5. At presentation, are the current classifications of severity of slips adequate? There is often a dilemma to pin in situ or to do open reduction for upper end of moderate and severe slips, because these can be biomechanically unstable if fixed with one pin? The treating surgeon ponders, will I be able to pin this in situ, and if not do I have the skills to open it? How does

one plan for this, because current classifications of slips are not predictable and reliable due to the way x-rays are taken? Should one hazard a frog lateral x-ray to classify the severity of slip in acute, acute on chronic or unstable slip and risk iatrogenic further displacement and exacerbate the risk of AVN?

6. Open reductions are done for severe SCFE. Often with this grade of SCFE surgeons wonder which is the best open technique? Is surgical dislocation technique the holy grail?

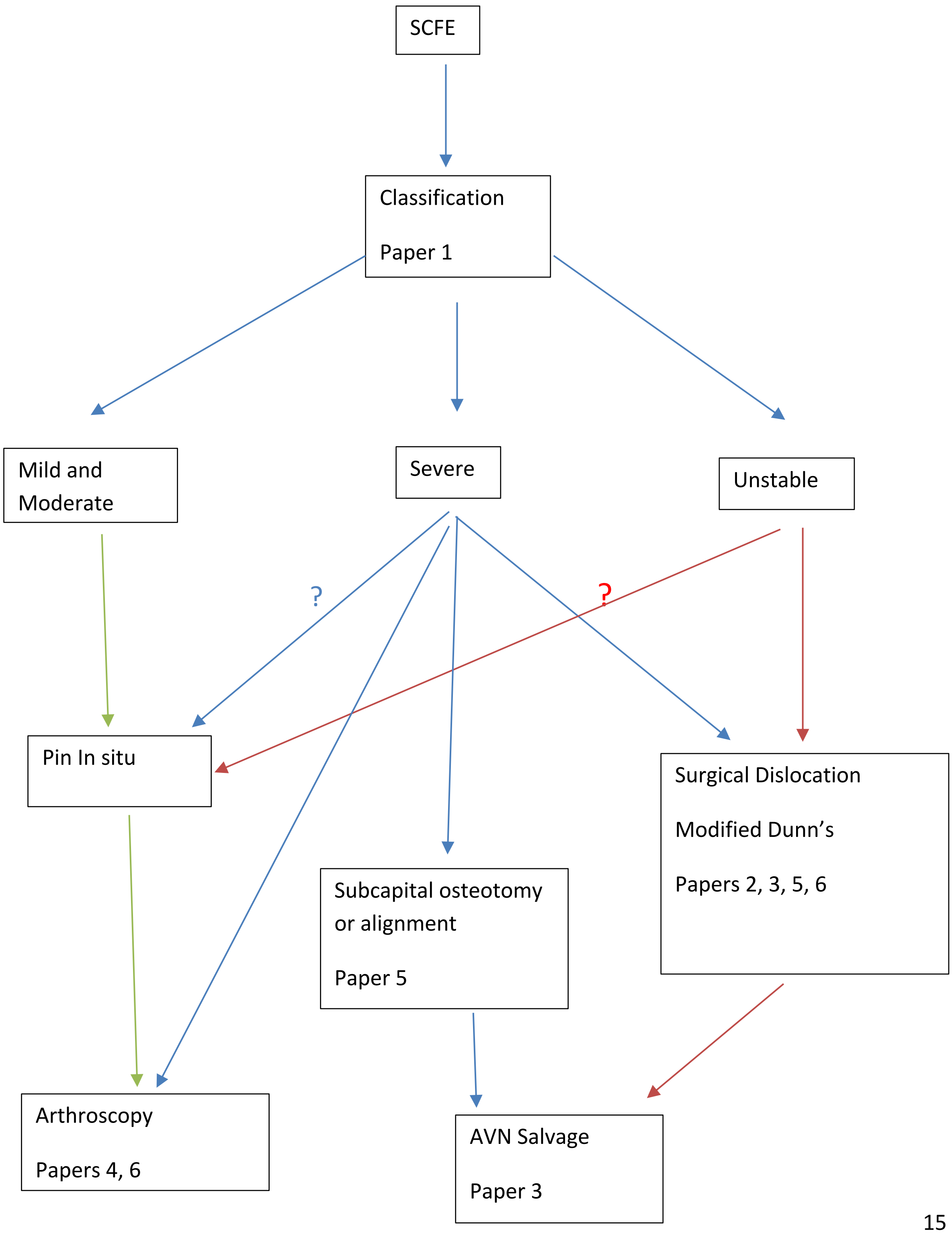
To address some of these problems, I embarked on a journey to treat this condition with the newly acquired skills of hip preservation surgery. This was a different and sometimes unconventional way to address and manage this problem. Over the years, I treated these cases, evaluated their clinical and radiological outcomes, and modified my approach as I went along. At the same time some leading centres around the world also started reporting their results and this became a useful comparator of outcomes for my cohort. These gave rise to 8 publications in SCFE. I have shortlisted 6 publications for my thesis. The two that I left out are extensions of the same theme of my included publications.

I have arranged the narrative in 6 chapters to cover the publications. They are a theme of managing various facets of SCFE presentations, with techniques that endeavour to restore the anatomy of the hip, in the hope that it is preserved in the long term. My discussions have been complementary and not repetition of my paper. I have discussed the literature and background with more papers that were published before and since my publications. Most of this was reassuring to know that I was on the correct path and in sync with rest of the other centres of excellence. Most of these studies were from Switzerland where hip preservation surgery was pioneered, and others were from leading paediatric orthopaedic centres in North America.

In my thesis, I start with the proposal of novel classification and build up from there the surgical dislocation technique and its use to manage various facets of SCFE presentation. As my career progressed, I became skilled in hip arthroscopy. Like other hip preservation surgeons, it is acknowledged that arthroscopic skill has a long learning curve. I took nearly 4 years to become skilled in this surgery and by 2010 could do a successful osteochondroplasty for all grades of deformity in SCFE. I then in my final paper embark on comparing open vs arthroscopic technique for severe grade of SCFE and discuss its outcomes and limitations. In the following chapters, I have retained some aspects of methodology and results from my publications submitted with this thesis, to keep the flow for the reader and maintain relevance to literature.

Linking papers on a theme of managing SCFE

Legend: It is necessary to establish severity of SCFE deformity with a classification which we proposed in paper 1. Depending on the instability and severity, patients were treated with anatomical reduction with surgical dislocation (paper 2 and 5). Complication like AVN was dealt with in a unique manner and the outcome was studied in paper 3. Sequelae of SCFE deformity was treated with arthroscopy and open surgery and its outcome studied in papers 4,5 and 6.



Literature Search:

1. Web of Science database

	Searches	**Results**
1	Slipped*	4668
2	Capital*	286601
3	Upper*	760884
4	Femoral*	127038
5	Epiphysis*	5753
6	1+2+4+5	1426
7	1+3+4+5	221

2. Medline

	Searches	Results
1	Slipped*	9094
2	Capital*	895980
3	Upper*	366226
4	Femoral*	210207
5	Epiphysis*	21554
6	1+2+4+5	1651
7	1+3+4+5	260

3. Cochrane database

	Searches	**Results**
1	(slipped):ti,ab,kw	67
2	(capital):ti,ab,kw	1147
3	(upper):ti,ab,kw	43689
4	(femoral):ti,ab,kw	13572
5	(epiphysis):ti,ab,kw	85
6	1+2+4+5	7
7	1+3+4+5	1

4. Starplus University Library Discovery

	Searches	**Results**
1	Slipped*	370618
2	Capital*	6142182
3	Upper*	6846075
4	Femoral*	447589
5	Epiphysis*	38271
6	1+2+4+5	3698
7	1+3+4+5	1394

Chapter 4: Novel Classification

Abstract

Background: Slipped capital femoral epiphysis (SCFE) is commonly treated with in situ pinning. However, a severe slip may not be suitable for in situ pinning because the required screw trajectory is such that it risks perforating the posterior cortex and damaging the remaining blood supply to the capital epiphysis. In such cases, an anteriorly placed screw may also cause impingement. It is also possible to underestimate the severity of the slip using conventional radiographs. The aim of this study was to describe and evaluate a novel method for calculating the true deformity in SCFE and to assess the interobserver and intraobserver reliability of this technique.

Methods: We selected 20 patients with varying severity of SCFE who presented to our institution. Cross-sectional imaging [either axial computed tomography (CT) scans or magnetic resonance imaging (MRI) scans] and anteroposterior (AP) pelvis radiographs were assessed by four reviewers with varying levels of experience on two occasions. The degree of slip on the axial image and on the AP pelvis radiographs were measured and, from this, the oblique plane deformity was calculated using the method as popularised by Paley. The intraclass correlation coefficient (ICC) was calculated to determine the interobserver and intraobserver reliabilities between and amongst the raters. Results The interobserver reliability for the calculated oblique plane deformity in SCFE ICC was 0.947 [95 % confidence interval (CI) 0.90–0.98] and the intraobserver reliability for the calculated oblique plane deformity of individual raters ranged from 0.81 to 0.94. The deformity in the oblique plane was always greater than the deformity measured in the axial or the coronal plane alone.

Conclusion: This method for calculating the true deformity in SCFE has excellent interobserver and intraobserver reliability and can be used to guide treatment options. This technique is a reliable and reproducible method for assessing the degree of deformity in SCFE. It may help orthopaedic surgeons with varying degrees of experience to identify which hips are suitable for in situ pinning and those which require surgical dislocation and anatomical reduction, given that plain radiographs in a single plane will underestimate the true deformity in the oblique plane.

Purpose of study: Current classifications are inaccurate and not usable. These cause significant practical issues. We proposed a new classification and assessed its reliability to see if it was practical and usable.

In-situ pinning for mild SCFE is a standard practice but for moderate to severe SCFE Surgical Hip Dislocation (SHD) is preferred in specialist centers[36]. There are several reports about screw failure and hardware problems associated with single cannulated screw in situ fixation[37–41]. Balakumar et al[42] showed impingement, progression of slip, fracture, and avascular necrosis due to metaphyseal penetration of the screw.

Therefore, it was obvious that there was a need of accurately assessing the 3D displacement of proximal femoral epiphysis in SCFE. The entry point for in situ single screw fixation must be placed far proximally or anteriorly on the femoral neck. This causes issue of impingement and significant restriction in flexion of the hip[43]. In severe slips the fixation screw has to pass the metaphysis have centre to centre position in femoral head in both views of radiograph, should be perpendicular to physis, should have at least 5 threads in the epiphysis, should be 5 mm from subchondral bone and not too far anterior in the femoral neck for biomechanical stability[42,44,45]. It is impossible to achieve all these prerequisites for a good fixation in moderate to severe SCFE. This leads to biomechanically unstable situation which is fraught with further complications.

There is significant limitation in achieving ideal entry point of screw in moderate to severe cases. Screw insertion site too far anterior can cause impingement in 50 to 70 degrees of flexion and obligatory external rotation[43]. The screw head also can cause significant damage to the labrum and chondral surface at the edge of acetabulum. It has been recommended that entry point should be lateral to the intertrochanteric line for stability. However, this can pose an issue in severe slips to achieve all metaphyseal trajectory to get to the centre of the femoral head and be perpendicular to the physis. To achieve the latter there is a significant risk of the screw penetrating out of the femoral neck posteriorly before entering into the epiphysis[46]. The main and predominant blood supply to the proximal epiphysis is from the posterior and lateral retinacular vessels[47]. Therefore this penetration of the screw can cause avascular necrosis[42,46].

Screw entry proximal to intertrochanteric line in the anterior part of the neck poses other problems. The metaphyseal bone is weak and so if the screw threads are adequate in the epiphysis then with the cantilever direction of force on the femoral head being inferior, lateral and posterior will move the shaft of the screw in the femoral neck thus causing progression of slip[48,49]. Balakumar et al[42] reported a fracture of the neck of femur due to stress shielding at the entry point of the screw.

Maletis and Bassett[41] observed in three cases that because the screw was greater than 1.5 cm prominent at anterior and lateral insertion site, the soft tissue stresses with movement caused the screw threads to become loose in the epiphysis. Screw fracture and failure is also another complication noted with this abnormal entry point issue and forces on the hip[39,40].

The diagnosis of severity of slip, on presentation, with current methods, has significant limitations. The diagnosis is based on plain radiographs. One of the most common classifications was described by Southwick who measured degree of slip as the difference in head shaft angle between the affected and the unaffected side in frog lateral position. He classified them as mild < 30 degrees, and severe > 50 degrees[50–52]. Wilson classified the displacement of femoral head on neck as mild < 33% moderate: 33-50% and severe > 50%[53–56]. A supine radiograph of pelvis underestimates the degree of slip. Obtaining a frog lateral view is difficult in a painful hip and if there is instability, it can cause issues with further displacement[57]. Billing's method of lateral radiograph is considered to detect mild contralateral slips[58,59]. This view involves again significant external rotation of the hip with having the same drawback. Moreover Loder has questioned the accuracy of Billing method and described limitations of frog lateral and cross table lateral views[60]. The cross-table views are difficult to obtain and not very clear because of the soft tissues and pose risk of radiation to gonads. Often these children are overweight which makes it even more difficult to see the true deformity in lateral plane. These methods on plain radiograph, only give uniplanar view of the deformity. The SCFE deformity is usually a posterior, inferior displacement with medial rotation of the epiphysis causing a varus (rarely valgus), extension, and external rotation deformity. To capture the true deformity, one must consider the direction of trajectory of this displacement and measure the magnitude of severity of the displacement.

Therefore, it is essential to obtain two orthogonal views to calculate the true magnitude and direction of slip. In our novel classification, consideration was given to calculate the oblique plane of displacement of epiphysis by a AP view and axial CT scan view to obtain orthogonal views to calculate true magnitude and direction of the slip[57,61]. We used the coronal plane view from AP radiograph to measure the angle x (x-axis displacement) and transverse plane image from axial view of CT scan or MRI scan to measure the angle y (y-axis displacement) of the epiphysis. From this we can derive the angle z as true magnitude of the deformity.

The oblique plane deformity is calculated using the formula

$$z = \arctan \sqrt{(\tan^2 x) + (\tan^2 y)}$$

The interobserver reliability as measured by ICC showed excellent correlation (0.947) for the oblique plane calculation between all four observers for first reading (publication 1).

The intra-observer reliability was good to excellent for all values, with a range from 0.800 to 0.968 ($p<0.001$) for all values and a range from 0.814 to 0.941 ($p<0.001$) in the oblique plane.

Spread of oblique plane calculations showed that there was no correlation between the seniority of the observer and the spread of values, with the lowest spread being from the two most junior raters.

The ICC values of 0.964 and 0.914 proves that our method of measuring the deformity in coronal and transverse plane respectively is classified as almost perfect agreement[62]. Combining the two methods to obtain oblique plane measurement also had near perfect agreement (ICC 0.947) which calculated the magnitude of slips in 20 hips examined. In our study, the observers had a varied experience viz. from varying degrees of trainees to senior orthopaedic consultant. This spread makes this classification more applicable in practice because it can be reliably repeated. The intra-observer reliability of test and retest done 6 months apart, with no further training given to the raters also had substantial to almost perfect agreement.

Obtaining shoot through or cross-table lateral view radiographs is associated with substantial soft tissue shadow[63]. The patients with SCFE usually have high body mass index[64] and therefore lateral radiograph is difficult to interpret[65]. None of the lateral views can give a true orthogonal view to measure the magnitude of deformity with AP view measurements. Therefore, we chose to obtain axial view CT scans for the geometrical method of calculating the true deformity in the correct oblique plane. This classification gives us the magnitude and the true plane of trajectory of the slip. This gives us the true posterior angulation and torsional component of the deformity.

We did not use the coronal plane CT scan for measurement because we wanted to make this classification workable in practice. The patients present to emergency department will have pelvis AP x-rays. We can then get a limited view CT scan along the plane of the neck axis thus minimising radiation dose. In our study, the mean angular deformity (66^0, range 43-83) in axial plane was twice that of the mean coronal plane deformity (33^0, range 4-63). The mean oblique plane deformity was even higher at (75^0, range 43-98). This study shows that the radiographs underestimate the magnitude of deformity.

Other authors have alluded to the value and accuracy of measuring the deformity using CT scan[63,66,67]. However, using CT scan routinely is difficult in clinical practice and a complete CT scan can increase radiation. Therefore, this has never taken hold in clinical practice. Our method of classification circumvents the problem of radiation dose and makes it easy and valuable in decision making. We have used this method for several years for moderate to severe SCFE and have found it extremely useful.

Our novel method of classification has subsequently been evaluated and independently found to be a useful classification. Datti et al[56], studied our classification with Southwick and Wilson classification using CT scans and found it to be accurate. Other authors are now increasingly using CT scans for decision making since our publication[68,69]. The issue with these is that the patients are subjected to significant radiation. With our method we maintain accuracy, ease of obtaining images, accurate to use by orthopaedic surgeons of varying degree of experience and very applicable in daily practice.

Our study had limitations. The number of cases were small. They all represented moderate to severe SCFE and therefore there wasn't a significant heterogeneity of values in our samples.

In this study of new classification, we showed that measurements were reproducible by clinicians with varying grades of expertise. However, this is a reliability study. We did not compare this classification to a gold standard such as Southwick's classification. Neither did we measure the magnitude and direction of slip intra-operatively at time of surgical dislocation to validate our results. This was another limitation of our study.

Chapter 5: Surgical Dislocation and Modified Dunn procedure for severe SCFE: Evaluation of new approach.

Abstract

We present our experience of the modified Dunn procedure in combination with a Ganz surgical dislocation of the hip to treat patients with severe slipped capital femoral epiphysis (SCFE). The aim was to prospectively investigate whether this technique is safe and reproducible. We assessed the degree of reduction, functional outcome, rate of complications, radiological changes and range of movement in the hip. There were 28 patients with a mean follow-up of 38.6 months (24 to 84). The lateral slip angle was corrected by a mean of 50.9° (95% confidence interval 44.3 to 57.5). The mean modified Harris hip score at the final follow-up was 89.1 (SD 9.0) and the mean Non-Arthritic Hip score was 91.3 (SD 9.0). Two patients had proven pre-existing avascular necrosis and two developed the condition post-operatively. There were no cases of non-union, implant failure, infection, deep-vein thrombosis, or heterotopic ossification. The range of movement at final follow-up was nearly normal. This study adds to the evidence that the technique of surgical dislocation and anatomical reduction is safe and reliable in patients with SCFE.

Incidence of slipped capital femoral epiphysis (SCFE) is increasing in certain population groups and is shown to be strongly associated with childhood obesity.[70–74] The incidence of SCFE peaked in Scotland in 2001 and thereafter has been stable and the incidence of obesity had peaked in 2004.[75] Perry et al[75] showed strong association of pre-disease obesity and social deprivation.

In the previous chapter we alluded to the deformity classification to assess the true magnitude and direction of slip. However, there are clinical classifications of presentation which can have significant bearing on outcome. An acute slip is considered presenting suddenly with less than three weeks history of symptoms.[76] Chronic slips present with gradual and insidious onset of symptoms of greater than three weeks duration and acute on chronic have preceding greater than three weeks of gradual onset of symptoms and then present with acute exacerbation.[77,78]There is also category of pre-slip with patient symptomatic but radiographs could be normal or there could be widening of the growth plate but no displacement.[79] This classification doesn't help in decision making, although it alludes to the acute slips, a proportion of which could have vascular issues to the femoral head. Loder[80] proposed a classification of stable and unstable slips. Unstable slips were when patient could not weight bear even with crutches.

We alluded to the problem of in-situ single screw fixation for severe and some moderate slips in the previous chapter. There is significant controversy regarding management of severe grades of SCFE, stable or unstable.[81,82] The deformity in SCFE leads to significant issues at the head neck junction with cam femoro-acetabular impingement (FAI) resulting in significant damage to the articular surface of the acetabulum.[83–85] Whereas there is potential of some remodelling in mild slips controversy remains about potential for remodelling in moderate to severe slips.[86–88]Whilst the remodelling takes years to happen, the metaphyseal prominence of femoral neck causes significant damage to the joint cartilage.[83,85] The thickened part of the remodelled femoral neck can cause significant insult at the chondro-labral junction of the acetabulum.[86,89] This can lead to early osteoarthritis.[90] Restoration of the head neck offset by resection of bone may help in minimising cartilage wear.[88,91–93]

Trueta[94] described the changing vascular supply of proximal femoral epiphysis during growth and its vulnerability in SCFE, Perthes and congenital dislocation of hips. This work illustrated subsynovial and intracapsular vascularity rather than the extracapsular course and vascularity of femoral head. Gautier et al[95] described the extracapsular course of predominant blood supply to the femoral head. This helped Ganz to develop the safe surgical dislocation technique for approaching the hip for several intracapsular pathologies and fractures.[96] He used this technique to anatomically reduce and fix the proximal femoral epiphysis.[88,97]Slongo et al[98] from same centre in Berne also described this technique. Because there was not much reported about the outcome of this technique from other centres outside Switzerland, we embarked on evaluating our results using this technique for unstable and stable SCFE of moderate to severe grades using surgical dislocation technique.

Dunn[99]had described this open technique of reducing and fixing femoral head epiphysis, and Ganz modified it by adding surgical dislocation approach. The procedure is done in a lateral position. Incision is straight lateral and is about 15-20 cm centred over the tip of the greater trochanter, one-third posterior of the width of the greater trochanter from anterior margin. After going through the fascia, gluteus maximus is dissected off the tensor fascia lata (TFL) and distally the fascia is split. Posterior border of gluteus medius is identified and dissection is done over and posterior to the greater trochanter to identify gluteus minimus, piriformis, superior gemellus, obturator internus, inferior gemellus, quadratus femoris, and gluteus maximus attachment to the femur (Fig 1). The piriformis and deeper to that the obturator externus protects the posterior ascending branches of the medial circumflex femoral artery (MFCA) that supplies the femoral head. With the leg in internal rotation, if possible, greater trochanteric flip osteotomy is done about 1.5 cm thick, flush with the shaft of the femur, extending from posterior border of the gluteus medius to the vastus ridge and elevated anteriorly (Fig 2). Gluteus minimus is dissected medially off the capsule and vastus lateralis is peeled off anteriorly. A z-shaped capsulotomy is performed from beyond the rim of the acetabulum along the length of superior and anterior border of the femoral neck and one arm of z is along the base of the femoral neck and other runs along the rim of the acetabulum posteriorly (Fig 3). With leg in internal and external rotation periosteal sleeve is developed from just below the lesser trochanter up the femoral head. This periosteal sleeve is dissected circumferentially off the proximal femur, and at the level of posterior and superior part of the bed of the greater trochanter osteotomy is done so that posterior and superior part of the femoral neck is flush with the shaft. The bone is filleted off the periosteal sleeve with great care. A hole is made with 2 mm drill bit in the bare area of epiphysis from where the periosteal sleeve has been ripped off to observe for bleeding. Two guide pins are inserted through the femoral neck into the femoral head and hip is subluxed and ligamentum teres is cut, and hip dislocated carefully with a hook. The upper femoral epiphysis is dissected off the femoral neck (Fig 4). The femoral neck is shortened by 1 to 1.5 cm and the upper femoral epiphysis, after curetting the growth cartilage, is anatomically reduced over the femoral neck without tension on the retinacular sleeve (Fig 5). Two guide pins are inserted from laterally into the epiphysis and under fluoroscopy two 6.5 mm cannulated screws are inserted (Fig 6). If possible periosteal sleeve is sutured and then the capsule is closed. Greater trochanter is fixed with two 4.5 mm or 3.5 mm cortical screws back onto the femoral shaft (Fig 7). Stability is checked and fascial and skin closure is done.

Fig 1. Shows piriformis tendon going under the gluteus medius.

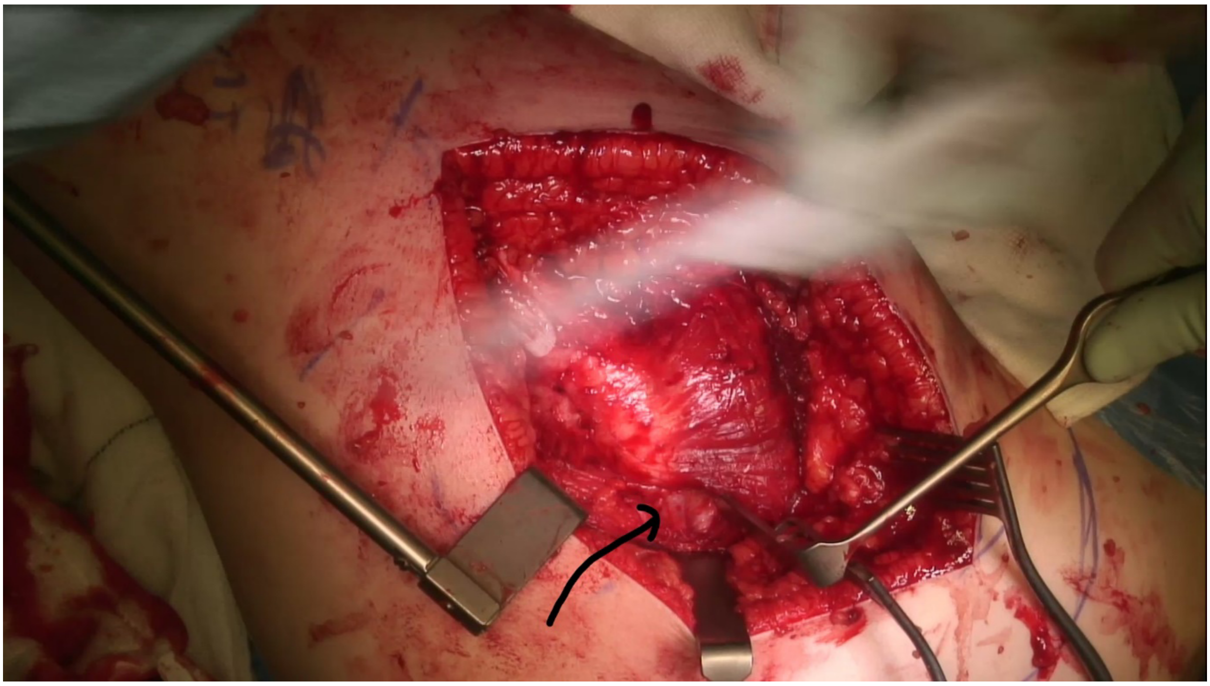


Fig 2. Few fibres of gluteus medius left attached after trochanter osteotomy.

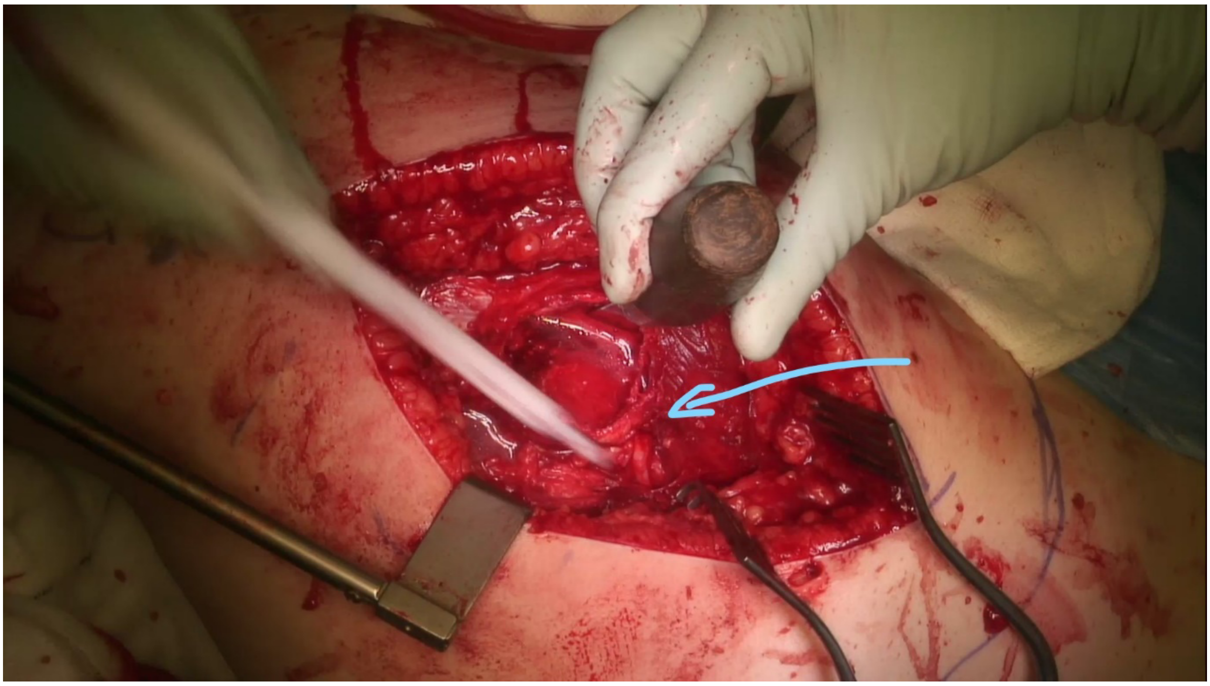


Fig 3. Capsulotomy. Blue arrow showing the femoral head under the labrum and black arrow shows the posterior capsule.

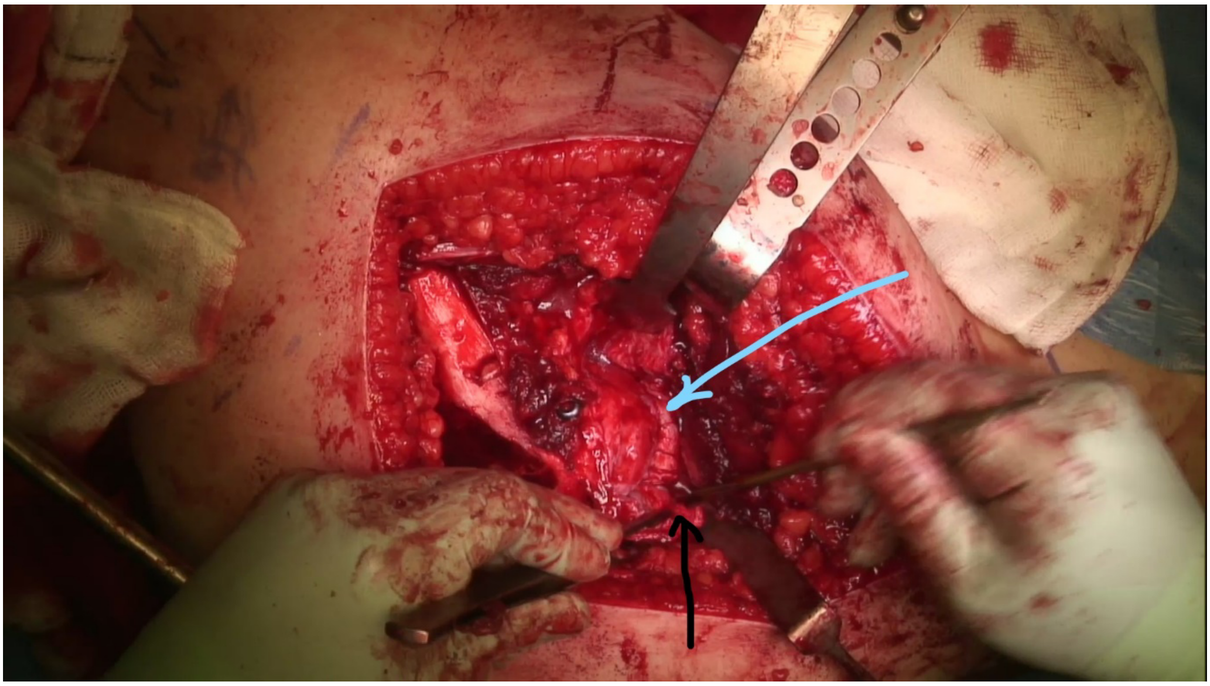


Fig 4. After separation of the femoral neck metaphysis (blue arrow) from the femoral epiphysis (black arrow).

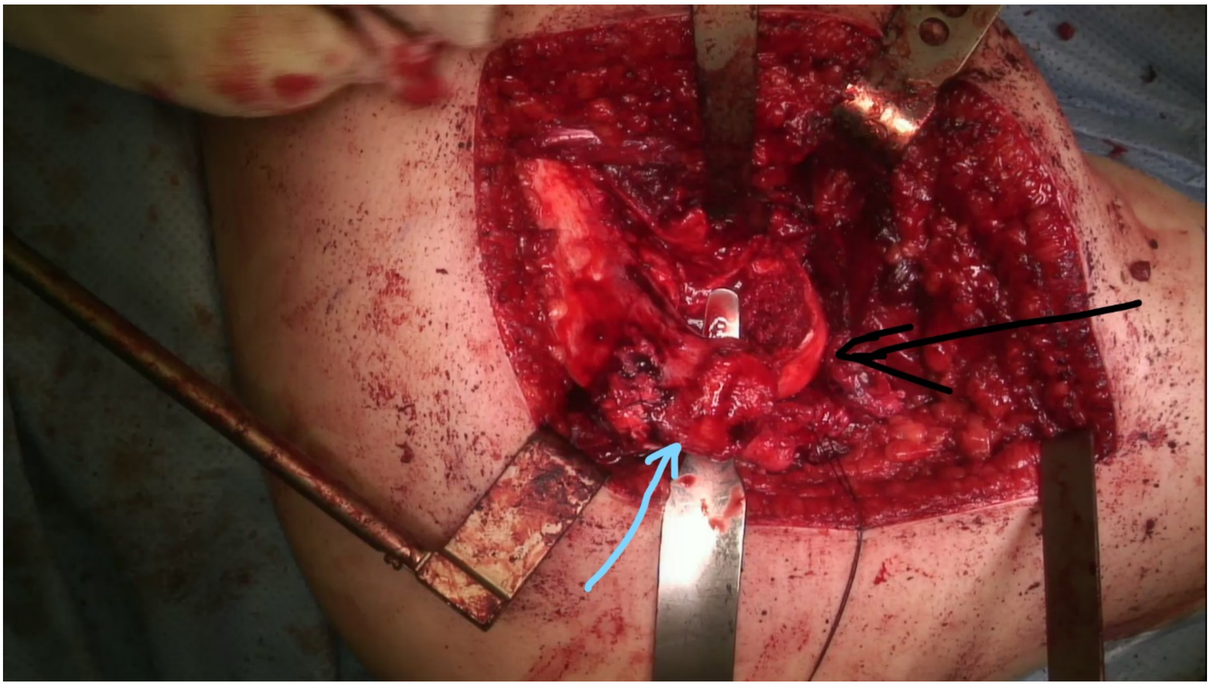


Fig 5. Femoral head (black arrow) reduced over the femoral neck and fixed with 2 guide wires.

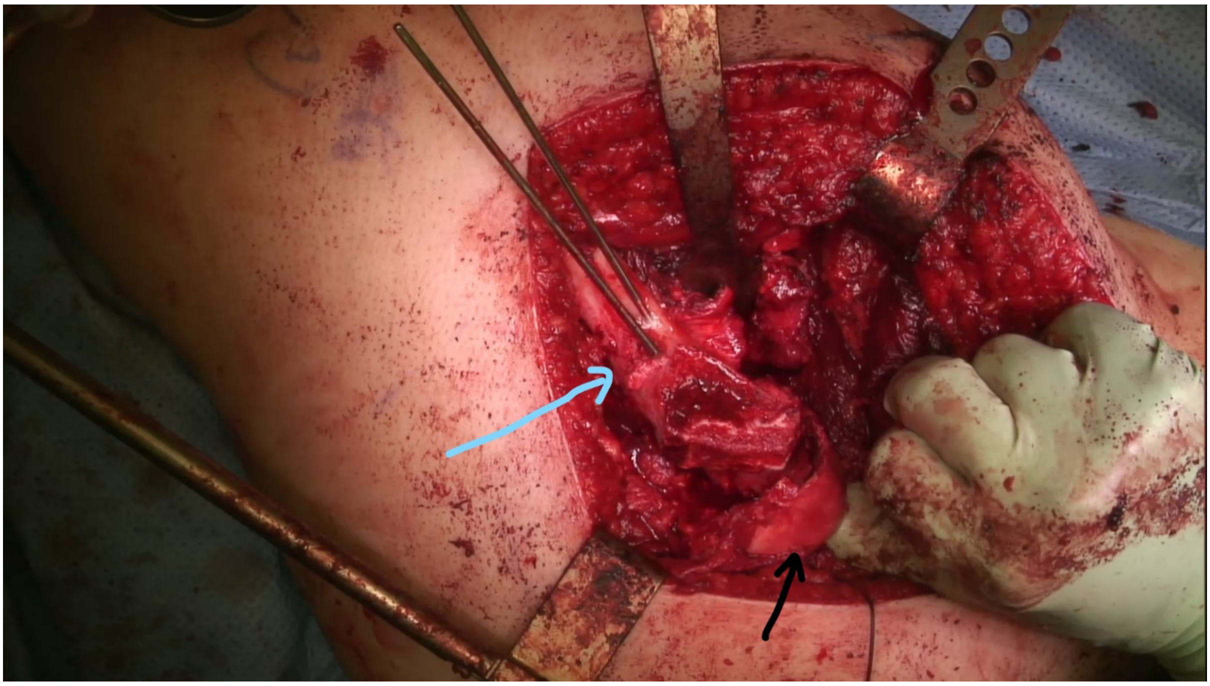


Fig 6. Cannulated 6.5 mm screws fixed in femoral head.

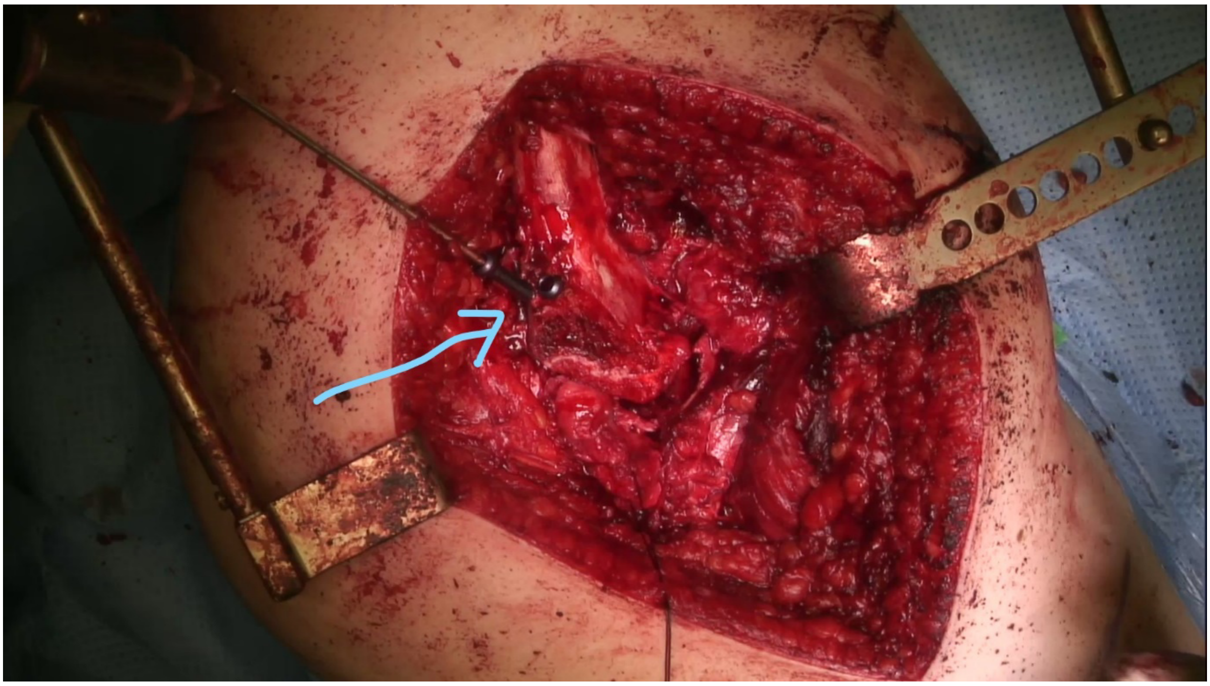
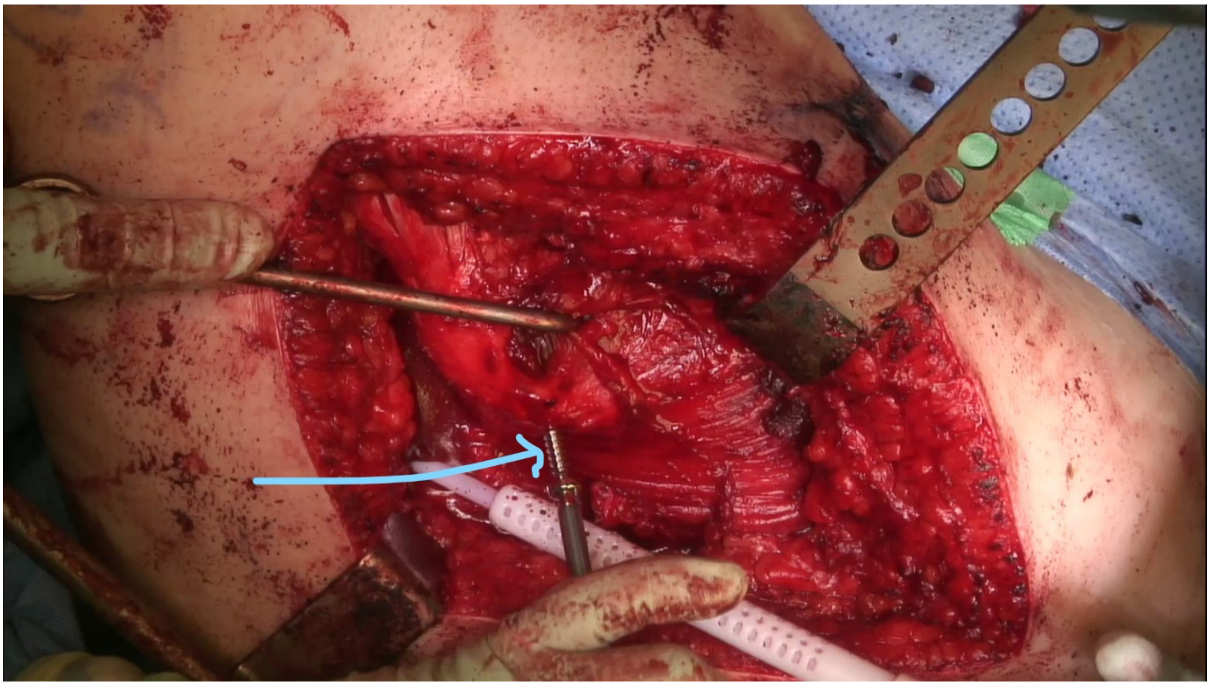


Fig. 7. Cortical screw fixed in greater trochanter.



For outcome measurement, Osteoarthritis was evaluated using the Tonnis grading[100] and AVN using Ficat classification.[101]

There was significant improvement in all ranges of movement at final follow up. (Table I).

Table I. The improvement of outcome scores (CI, Confidence Interval)

Score	Mean improvement	p-value (paired t-test)
MHHS		
Overall	68.3 (60.0 to 76.8)	<0.001
Unstable	82.3 (73.7 to 90.9)	<0.001
Stable	50.5 (43.9 to 57.1)	<0.001
NAHS		
Overall	68.1 (58.6 to 77.6)	<0.001
Unstable	81.9 (70.9 to 93.0)	<0.001
Stable	49.2 (41.4 to 56.9)	<0.001

Our rate of AVN attributable to surgery was 7.1%. This is comparable to other reports in literature.[88,98,102,103]

There are various techniques of open reduction for moderate to severe grades of slips. Dunn[99,104,105] described a technique of trochanteric flip osteotomy, with patient in lateral position, usually through the apophyseal growth plate and then dissecting the periosteal flap from the posterior part of the neck leaving it attached only to the femoral epiphysis. Thus, the neck is bare and can be shortened and repositioned on to the femoral head. The proximal femoral epiphysis is not detached from the ligamentum teres and the surgical dislocation is not done. This approach gives much better vision once the gluteus medius and minimus is elevated out of the way with greater trochanter. However, it is not as good as surgical dislocation, because it does not allow us to monitor the blood flow, by drill hole in the capital epiphysis. Full inspection of articular cartilage of femoral head and acetabulum is not possible. Unlike Ganz's modification of this technique, the posterior and superior bed of greater trochanter is not osteotomised and made flush with the shaft. The latter helps to reduce the tension on the posterior retinacular flap when the femoral head is reduced back on the neck. Unless this is done, a more generous shortening of the femoral neck is needed.

Fish[106–108] described a cuneiform osteotomy unlike Dunn's trapezoidal osteotomy as described above. He approached the hip through Watson-Jones approach.[109]A T-shaped capsulotomy is done and the femoral neck and head junction is identified. Then with an osteotome a crescentic shaped cuneiform wedge is removed usually based anteriorly and superiorly and the femoral head is reduced and fixed. His AVN rate was only 3 out of the 66 hips. He gave great importance to curette the growth cartilage off the metaphyseal face of the epiphysis to accelerate union and blood supply.

Parsch[103] described a technique of minimal intervention with open reduction. He also approached the hip through Watson-Jones approach.[109] He emphasized the importance of evacuation of the haematoma after capsulotomy and timing of operation as very important factors in lowering the incidence of avascular necrosis. After capsulotomy he felt the junction of the metaphysis and epiphysis and then with a finger gently pushed the metaphyseal back whilst putting the leg through abduction flexion and internal rotation to reduce the hip. He only attempted to reduce the acute and unstable element of the hip and accepted partial reduction so that it was possible to fix the epiphysis.

Biring et al[110] and Vaneghan et al[111] performed the Fish osteotomy technique through Smith-Peterson approach.[112,113] They also reported low rates of AVN in their series.

The surgical dislocation modification to Dunn's technique has several advantages over other techniques. It allows full circumferential view of the femoral head and acetabulum and permits addressing issues of labral and chondral surfaces of the hip joint. The periosteal flap attached to the femoral head can be inspected in its entirety. This is important because with all the other techniques described above the far side of the retinacular flap is not under direct vision and therefore inadvertent rents or damage can happen with osteotome, or callus while reducing the femoral head epiphysis. This approach is demanding and when this paper was published there were no single centre studies outside Berne that had reported this approach to anatomically reduce severe grades of SCFE. Shankar et al[114] collected 27 cases from 5 centres and for unstable slips and quoted 26% AVN rate. The issue of AVN and outcomes as to the approach of reduction will be discussed in the next few chapters.

Our series showed that this approach is safe and functional outcome is good to excellent. Tosounidis et al[115] showed no relationship to the approach of the hip and subsequent development of AVN. They reported a weighted risk of AVN as 5.3% with a 9.4-fold increase in risk for unstable slips.

There are complications reported of screw or pin failure.[114,116] We used two 6.5 mm cannulated cancellous screws for fixing the capital epiphysis and two 4.5 mm cortical screws to fix the greater trochanter. We had no implant failure or non-union. One of the devastating complications is dislocation or subluxation of the hip.[117–119] Although we did not have this in our series, subsequently we have had two subluxations that we treated with arthrodiastasis using hinged distraction.

After evaluating the surgical dislocation technique, ourselves, we find that it is effective in treating patients with severe grades of stable and unstable hips. This approach allows for anatomical reduction at centre of rotation of angulation, corrects the femoroacetabular impingement and external rotation deformity of the hip, and addresses the labrum and joint cartilage.

Surgical dislocation is one method of treating SCFE. This was a case series but from this study we couldn't say that our results are superior or inferior to other open techniques of treating this condition. There was a lack of a comparative method in this study. We could have compared this result with another method of open technique done by another expert who is skilled in that method. Because open reduction is challenging, surgeons, in general terms, stick to one method of treating this condition. Limitation of our study was lack of comparing our method to another established method of open surgical technique.

Chapter 6: Managing severe deformity with instability- Evil of Avascular Necrosis- Novel approach

Abstract

Background: Management of avascular necrosis (AVN) of the femoral head in slipped capital femoral epiphysis (SCFE) is difficult. We proposed to ascertain if staged hip distraction could prevent collapse and recover the femoral head.

Methods: A retrospective review of the hip database retrieved 16 children with unstable SCFE and AVN. All underwent capital realignment by surgical dislocation followed by 2nd-stage hinged hip distraction. Patient demographics and radiographic parameters of deformity, AVN and arthritis were collected. The patients scored their hip function both before and after intervention and at follow-up using the modified Harris Hip Score and Nonarthritic Hip score.

Results: 7 boys and 9 girls formed the study group (*n* = 16). The average age at surgery was 12.7 years (9–16 years). 8 rights hips and 8 left hips were involved. The average follow-up was 45months (33–66months). Group A (*n* = 7) had hip distraction only if the follow-up radiographs showed AVN changes and collapse. Based on the observations in Group A, the protocol was changed for Group B. Group B (*n* = 9) underwent hip distraction at 6 weeks of capital realignment for avascularity of the femoral head. In Group A, all patients had further collapse and advanced arthritis at follow-up. In Group B all patients had hip joint space restored and good hip function without pain at follow-up.

Conclusions: Pre-emptive application of hip distractor for those children with proven lack of blood flow to the femoral head is a potential option to stall the progression of AVN and to help recover useful hip function.

Study Question: Can Avascular Necrosis secondary to SUFE hips be saved?

In this chapter we discuss issue of unstable slip and a novel strategy to reduce morbidity of avascular necrosis (AVN).

Loder et al[80] classified slip as unstable when the child, because of severe pain, was unable to weight-bear even with crutches. He showed an AVN rate of 47% in 30 unstable slips of which most (except two requiring open reduction) were inadvertently reduced closed and fixed in-situ. They found on an average there was 61% reduction with acute slips. Twenty-seven (90%) of their cohort of unstable slips had presented after a fall. This shows the true high energy trauma to the hips. Gage et al[120] reported the collective incidence of aseptic necrosis after osteotomy of the femoral neck in 393 hips reported on by twenty authors. The percentage of aseptic necrosis ranged from zero to 100, with an average of 21 per cent.

Closed manipulation.

Closed manipulation of severe unstable or acute slip, in order to make in-situ fixation possible, has high incidence of avascular necrosis from 10 to 60%.[52,80,121–129] However Hall[130] reported 3 cases of AVN in 33 acutely presenting slips. His recommendation was to manipulate as early as possible. On the other hand Fairbank[79] recommended manipulation for acute and acute on chronic slips but to only manipulate once with care. In their series of 35 manipulation internal fixation was done for 16 hips. He reported no cases of AVN. From the review of literature, it seems that manipulation is not a reliable procedure as force required to reduce can be excessive and can tear the posterior sleeve of the retinaculum. In fact his has been observed with over correction which can lead to AVN.[126,131,132] Walton et al[132] showed there was 80% incidence of AVN with complete closed reduction and pinning. They showed pinning in situ after incomplete reduction led to 33% AVN. Griffith[133] manipulated 29 of the 44 acutely presenting hips and could get 11 improved. He found that 8 of the 11 develop AVN (73%). There was no AVN in the remaining 18 hips in which the position remained unchanged after manipulation. There was only one AVN in the remaining 15 hips and that had been reduced by traction. With the severity of slip, pinning in situ is difficult and carries the risk of posterior penetration of the femoral neck before entry of the screw into the femoral head.[42,134,135] (Fig 1 and Fig 2).

Open Reduction

Therefore, it has been proposed that severe slips should be treated with open reduction. In this chapter we will deal only with acute and unstable slips. Chronic slips will be dealt in the other chapter. Rates of AVN have varied with open reduction of unstable slips and acute slips. Parsch et al[103] treated 64 unstable slip with open reduction of the slips. In their cohort 20 slips were mild and 24 of moderate degree of slip. Twenty patients had severe degree of slip. Half of their cohort could have been treated with pinning in situ. The author also admits that they have not adhered to the true classification of instability as proposed by Loder.[80] They state that 9 of the 20 mild slips wouldn't be classed as unstable as per Loder's classification because they could weight-bear albeit with pain. This has also been a major issue of what is a true unstable hip and what is classed as acute or acute on chronic slips.[76–78,136] Most of the series have been retrospective and therefore there is considerable spread of rates of AVN in open reduction as is in closed reduction for unstable SCFE.

Closed or open reduction for only Unstable slips

Several open techniques have been described for SCFE, but they have been for a mix of unstable and stable SCFE.[88,98,107,110,134] However, recently attempt has been made by authors to report outcomes of unstable slips as separate group with significant rates of AVN. Sankar et al[129] reported AVN rates of 19% in patients pinned in situ, 26% in those with gentle or inadvertent reduction and in 6% with open reduction for unstable slips. In another multicentre series of 5 experienced centres Sankar et al[114] reported an AVN rate of 26%. Walton et al[132] reported an AVN rate of 42% undergoing pinning in situ compared to 25% undergoing open reduction. Madan et al[137] reported a rate of 7.1% AVN for unstable slips after excluding patients who were proven to have AVN pre-operatively on radioisotope bone scan. Persinger et al[138] had 6% AVN rate in their consecutive series treated with modified Dunn procedure. Wenger and Bomar[139] had reviewed several studies and concluded that pinning in situ could have AVN rate for unstable slips between 20% to 50%, and with modified Dunn procedure it could be up to 25%.

Timing of reduction

The timing of closed or open reduction for unstable SCFE has been studied. Fairbank[79] and Hall[130] have reported a 0 to 9% AVN rate for early gentle manipulation of severe acute SCFE. Loder et al[80] reported that the hips that were operated upon on an average 4 days from the onset of symptoms developed AVN and those operated later than 12 days did not. They found that 4 of the 5 hips (80%) that were operated within 24 hours of their onset of symptoms developed AVN. Phillips et al[140] in a their report of 100 cases had no AVN in the 14 unstable hips that were treated with closed reduction and pinning within 24 hours, and had 4 AVN in 86 stable hips pinned in situ. Peterson et al[141] reported 7% AVN when treated with 24 hours with closed reduction as opposed to 20% AVN when reduced after 24 hours. Walton et al[132] reported that emergency pining after closed reduction had 67% rate of AVN when done on 2nd or 3rd day after presentation. Open reduction with cuneiform osteotomy done > 13 days after presentation showed no AVN (5 hips). They recommended non-emergency pinning in situ to be done after 5 days and open reduction to be done after 14 days.

Our Study

It is inevitable that unstable SCFE will have an incidence of AVN. The question was can we salvage these hips effectively and prevent inevitable and imminent Osteoarthritis. To address this objective, I introduced a novel approach of salvaging this hip in the medium term. My objective was to see whether arthrodiastasis

with an articulated (hinged distractor) monoliteral fixator, one could salvage these hips. Between October 2006 to October 2014, we identified 30 cases of arthrodiastasis from our limb reconstruction database. There were 17 hips with SCFE that had this treatment. One of these had chondrolysis that was excluded from the study group.

Our centre has been performing arthrodiastasis mainly for patients with Perthes who have adverse prognostic indicators. We decided to transfer this practice to patients' presenting with unstable SCFE with proven diagnosis of AVN on perfusion MRI scan.[142] Our normal practice of arthrodiastasis for Perthes was to keep the fixator on for an average of 4 months. We also thought that after open reduction with modified Dunn procedure some of the femoral heads would salvage. Although we did post-operative MRI scans and or bone scan, we found that all the 16 patients had definitive or some reduced perfusion pre-operatively and at operation, and there was no bleeding on drilling the proximal femoral epiphysis (Fig 1 and 2). Post-operative MRI scan or bone scan was not conclusive of revascularisation. We used Titanium 6.5 mm cannulated screw fixation to minimise MRI scan interference. We found that no bleeding at the time of surgery was most conclusive of AVN which was also supported by reduced or no perfusion on pre-operative MRI scan. There have been studies looking at the sensitivity and specificity of the intra-operative findings of no bleeding with subsequent AVN.[143,144]

If the patients had no vascularity on pre-op MRI scan or Radioisotope bone scan, or was inconclusive but had no bleeding through drill hole at operation, then it was conclusive that there was AVN. In none of these scenarios in our cohort we saw post-operative MRI scan to show perfusion. However, we were yet expectant and thought that if we have first sign of conclusive evidence of AVN on radiograph we could perform arthrodiastasis. We found however if the femoral head had shown crescentic sign or there was early collapse, arthrodiastasis was unable to salvage the hips. After gaining such insight from the first 7 cases in Group A, we changed the protocol to group B where we decided to pre-emptively put the hinged distractor at 6 weeks after the surgical dislocation and anatomical reduction of the hip. We found from our experience from group A that the earliest sign of collapse of femoral head had happened 8 weeks after the surgical dislocation. Therefore, we thought it would be good to pre-empt this by arthrodiastasis at 6 weeks post index operation. It is not advisable to insert the fixator at the time of surgical dislocation because of obvious reasons that external fixator pins can cause secondary infection. It is to note that femoral head becomes soft when revascularisation process begins. We observed from our clinical experience that this would take 6 weeks or more. It is also to note that the half pins in pelvis can become loose and cause issues after prolonged periods of distraction. Therefore, to minimise this duration of external fixation, on balance, we thought applying the fixator at the right time when femoral head was getting soft would be prudent. We were successful in salvaging the hips in group B and restore near normal anatomy and function (Fig 3).

Fig. 1. Screw exiting the femoral neck

Fig. 2 Radio-isotope bone scan confirming AVN.

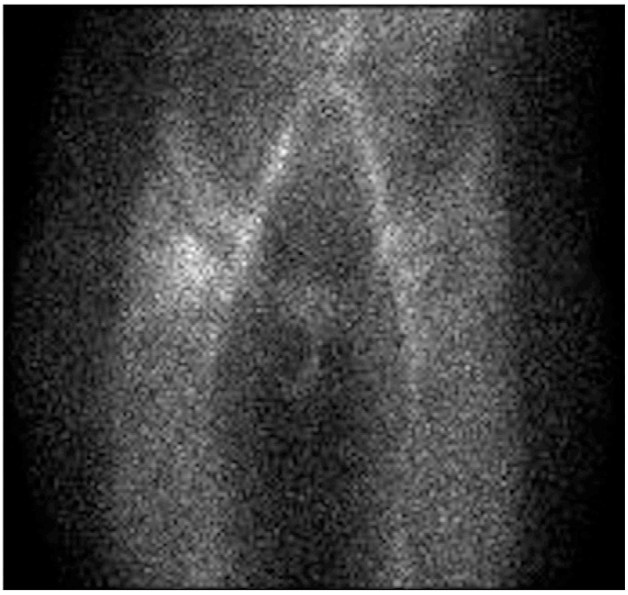
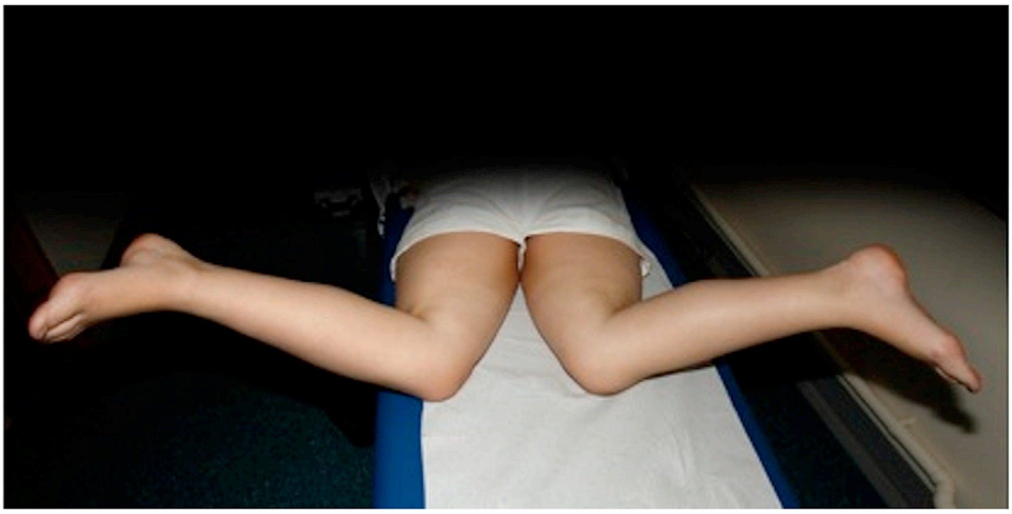


Fig 3. Normal range of movement



Hinged distraction allows movement of the joint, thus nourishing the articular cartilage with circulation of the synovial fluid, and at the same time produces distraction. This offloads the joint from the body weight and allows the joint cartilage to regenerate, protecting it from body weight and surrounding muscular forces. We showed that 56% had salvaged their hip, and until now, none of these patients have got significant deterioration in their clinical outcome.

Canadell et al[145] treated two patients with SCFE. Both patients had functional improvement. The duration of fixator was 90 and 78 days. Hinged distraction can maintain and preserve the joint cartilage.[146] In our group B we had 4 Tonnis grade 1 and 2 Tonnis grade 2 hips that were preserved. In 1994 Aldegheri et al[147] in a study of 80 cases had 15 patients with SCFE, of which 6 had arthrodiastasis alone, and rest had additional soft tissue release and limited arthroplasty. The fixator was kept on for between 6 to 10 weeks. We used this technique specifically for AVN. Older children and adults can take up to 2-4 years for revascularisation of femoral head. We have observed in Perthes disease that hinged distraction accelerates revascularisation in the femoral head, which is according to the principle of Ilizarov distraction histogenesis.[148,149]

Paley and Lamm[150] did a retrospective study of 16 cases, of which two were SCFE and rest were Perthes. Although they found improvement in pain and function, they concluded that after subchondral collapse, it was too late to show improvement with hinged distraction. This result was similar to our Group A cases. Gomez et al[151] evaluated the outcome of AVN for adolescent patients. Of the 31 hips studied, they had 11 cases of SCFE AVN. All these patients had pinning followed by distraction. They concluded that SCFE patients did not do as well. They, however, did observe improving trend with longer duration of hinged distraction. We have shown in our Group A series that shorter duration of distraction does not work. The fixator must be on until consolidation of lateral pillar. The dense head becomes radiolucent with vascularisation at the lateral pillar first and vascularisation thereafter progresses medially. It is safer to remove the fixator when lateral one third to half of the femoral head becomes radiolucent. This happened in our Group B patients in 10 to 12 months.

This is the first series that has shown success in salvaging hips that were doomed to failure. The sample size in each group was small. This wasn't adequately powered, although the clinical outcome was quite dramatic in two groups. Conclusions drawn from this small pilot study should lay some basis for a bigger study, to evaluate this method of salvaging avascular femoral heads due to unstable SCFE.

Chapter 7: Arthroscopy for Femoro-Acetabular Impingement (FAI) in SCFE

Abstract

Slipped capital femoral epiphysis (SCFE) may lead to symptomatic femoroacetabular impingement (FAI). We report our experience of arthroscopic treatment, including osteochondroplasty, for the sequelae of SCFE. Data were prospectively collected on patients undergoing arthroscopy of the hip for the sequelae of SCFE between March 2007 and February 2013, including demographic data, radiological assessment of the deformity and other factors that may influence outcome, such as the presence of established avascular necrosis. Patients completed the modified Harris hip score (mHHS) and the non-arthritic hip score (NAHS) before and after surgery. In total, 18 patients with a mean age of 19 years (13 to 42), were included in the study. All patients presented with pain in the hip and mechanical symptoms, and had evidence of FAI (cam or mixed impingement) on plain radiographs. The patients underwent arthroscopic osteoplasty of the femoral neck. The mean follow- up was 29 months (23 to 56). The mean mHHS and NAHS scores improved from 56.2 (27.5 to 100.1) and 52.1 (12.5 to 97.5) pre-operatively to 75.1 (33.8 to 96.8, $p = 0.01$) and 73.6 (18.8 to 100, $p = 0.02$) at final follow-up, respectively. Linear regression analysis demonstrated a significant association between poorer outcome scores and increased time to surgery following SCFE ($p < 0.05$ for all parameters except baseline MHHS). Symptomatic FAI following (SCFE) may be addressed using arthroscopic techniques and should be treated promptly to minimise progressive functional impairment and chondrolabral degeneration.

Take home message: Arthroscopy of the hip can be used to treat femoroacetabular impingement successfully following SCFE. However, this should be performed promptly after presentation in order to prevent irreversible progression and poorer clinical outcomes.

Study Question: Does hip arthroscopy address issue of femoro-acetabular impingement secondary to SCFE?

Femoroacetabular impingement (FAI) is a significant cause of Osteoarthritis (OA) of the hip.[152–157] The loss of femoral head neck offset causes a cam FAI. This causes abutment of the femoral head neck junction on acetabular margin in flexion and internal rotation of the hip. The Chingford study[158] was a prospective study of 1003 women followed up for 20 years. This study showed that for every 1^0 increase of alpha angle above 65^0 there was a 5% increase in radiographic changes of osteoarthritis and 4% increase in need of total hip replacement in the study period. The CHECK study[159] obtained baseline radiographs and then followed patients for 5 years and determined progression of radiographic hip OA in middle age patients presenting with hip pain. They also used the alpha angle on AP radiographs as their measure of cam-type FAI and found that an alpha angle >60 degrees had an adjusted odds ratio (OR) of 3.67 for the development of end-stage arthritis. An alpha angle >83 degrees had an adjusted OR of 9.66 for the development of end-stage arthritis over 5 years. When patients had both an alpha angle of >83 degrees and hip internal rotation in 90 degrees of flexion of <20 degrees the adjusted OR was 25.2 and a positive predictive value of 53% for the development of end-stage arthritis over 5 years.

Even mild SCFE is a severe form of FAI. As severity increases, the cam deformity worsens causing significant risk to the joint cartilage.[160–165] SCFE typically causes loss of internal rotation in flexion, or obligatory external rotation and severe cam FAI. Long term studies by various authors have shown significant progression to osteoarthritis.[166–171] The deformity has very little potential for remodelling, and the residual pistol grip deformity can cause early onset of osteoarthritis.[172–174] During the process of remodelling the femoral head neck junction becomes smooth and causes retroflexion.[100] This process is slow and by then significant damage is done to the osteochondral junction.[175–178] The deformity of SCFE is complex. Whereas there is loss of head neck offset, there is also associated retroversion, varus and extension deformity.[13,57,84,137] This leads to obligatory external rotation in flexion, limited abduction, loss of internal rotation, and external foot progression angle.

The asphericity of the femoral head abuts against the acetabular rim. This leads to partial tear in the labrum and secondarily there is mechanical injury to joint cartilage at the rim, causing, softening, delamination and flap tear of the cartilage.[154,155,179–182]

We hypothesised that perhaps the major issue was intra-articular pathology of the hip that caused secondary damage due to FAI and it was thought correcting this by minimally invasive approach could prevent further damage. The extraarticular effect of the deformity could be perhaps compensated and if not a rotational osteotomy of the femur could be undertaken later. Therefore, we studied our cohort of patients to see the clinical and radiological outcome in these group of patients.

Between 2007 to 2013 we prospectively studied 18 consecutive patients who underwent hip arthroscopy for sequelae of SCFE, to correct the cam FAI. All operations were done by me, at two sites: Sheffield Children's Hospital, and Doncaster Royal Infirmary.

The improvement in outcome scores, alpha angle and femoral head neck offset ratio is shown in Table I and II.

There was significant negative association between time from slip and patient related outcome scores (linear regression analysis). Increased time resulted in poor outcome both before and after surgery. There was no association between severity of slip and function.

Table I. Pre-operative and post-operative scores.

Mean mHHS (range)			Mean NAHS (range)		
Baseline	Post-operative	Improvement (p-value)	Baseline	Post-operative	Improvement (p-value)
56.2 (27.5 to 100)	75.06 (33.8 to 96.8)	18.86 (0.01)	52.07 (12.5 to 97.5)	73.58 (18.75 to 100)	21.51 (0.02)

Table II. Pre- and post-operative measurement of cam deformity.

	Pre-operative	Post-operative	p-value
Mean alpha angle (^{0})	91.61	51.73	0.0001
Mean head neck offset ratio	-0.015	0.113	<0.0001

Smith-Peterson in 1936 first described value of osteoplasty in old healed slipped upper femoral epiphysis to correct impingement.[183] Terjesen and Wensaas[171] followed up 60 hips for an average of 39 years. They showed that severe slips had poor modified Harris Hip score. 33% had poor outcome in their study. Goodman et al[184] studied femora in 2665 adult human skeletons. They found post slip morphology in 8%. They noted that severe osteoarthritis was present in 38% with slip morphology as compared to 26% with normal morphology. Ghijselings et al[166] in their minimum 18 year follow up study of 76 SCFE hips had 10 (15.6%) converted to a total hip replacement (THR) after a mean of 16 years. 38 (59.4%) patients underwent a clinical and radiographic examination after a mean follow-up of 23 (range 18–33) years. 12 (18.8%) patients were lost to follow-up. 74% of SCFE hips demonstrated degenerative change on radiography or were converted to THR (Tönnis 1: 33.3%, 2: 18.5%, 3 or THR: 22.2%). These studies affirm that SCFE cam causes significant OA in the long term.

The pattern of wear in SCFE is much different to other aetiology of OA of the hip. Abraham et al[185] showed that the SCFE group was characterized by (1) loss of neck-head offset, (2) acetabular neck impingement, and (3) loss of superior peripheral articular cartilage adjacent to superior neck. Whereas the primary OA group showed (1) preservation of head-neck offset, (2) absence of acetabular neck impingement, and (3) preservation of superior peripheral articular cartilage. The 3-D modelling in SCFE specimens demonstrated acetabular impingement on the superior lateral femoral neck causing the femur to externally rotate with flexion. The SCFE patients undergoing total hip arthroplasty on average were 11 years younger than those with primary OA. The study strongly suggested that the abnormal rotation of the femoral head in SCFE patients caused thinner superior lateral articular cartilage on the femoral head to articulate with the acetabulum.

Our study is comparable to other studies where arthroscopic osteoplasty was done with good result in the short term.[163,164,186,187] Unlike most other studies[163,187,188] we showed that arthroscopic osteochondroplasty is effective in improving pain and function even in severe grade of slips. We had 5 patients who had severe slips. Severe slips and some moderate slips have significant retroversion deformity. We thought that this would need correcting as a second stage with femoral derotation. However, to date all patients were satisfied and did not want any more surgery because they had significantly improved. This made me ponder that intra-articular damage to the hip was of major significance and that correction of extra-articular deformity would not matter so much and perhaps would be more of aesthetic value. In another chapter we will study this aspect in greater detail.

Chapter 8: Severe deformity correction: Different approach

Abstract

Purpose: Contemporary methods for management of neck deformity following a healed severe slipped capital femoral epiphysis (SCFE) include subcapital neck osteotomy.

Methods: 18 patients with chronic severe SCFE in the oblique plane (mean slip angle = 70º) constituted the study group. 6 patients with an open physis underwent modified Dunn capital realignment and 12 patients with a closed physis underwent surgical dislocation with a corrective neck osteotomy. 10 patients already had an in-situ pinning.

Results: The mean follow-up was 4.5 years (3-6 years). The mean preoperative modified Harris Hip Score (mHHS) and nonarthritic hip score (NAHS) were 24 and 40 respectively, followed by a score of 89 and 92 respectively at the last follow-up ($p = 0.0002$). Radiologically, all the parameters showed a significant correction. The mean pre- and postoperative values of alpha angle were 79.8 and 34.5 respectively ($p = 0.0002$); AP slip angle being 36.7 and 14.8 ($p = 0.002$); lateral slip angle being 54.2 and 13.6 ($p = 0.0002$); oblique plane slip angle being 70.7 and 20.8 ($p = 0.0002$) and centre trochanter distance being -6.9 and 1.2 ($p = 0.002$). The major complications seen were non-union of the neck osteotomy (n = 1/12) and chondrolysis (n = 1/16) in the modified Dunn's group. The overall complication rate was 11%. There was no statistically significant difference in outcome between the 2 groups clinically and radiologically.

Conclusions: Femoral neck osteotomy is a potentially rewarding technique to correct severe neck deformities and restoring hip function in the short term.

Study Question: Is femoral neck osteotomy or capital realignment procedure reasonable option for Severe Chronic SCFE

Several authors have discussed the cam FAI effect and its damage to joint cartilage for all grades of SCFE.[160,171,176,178] However, severe SCFE causes significant deformity affecting rotation, and gait abnormality.[189–191] Although hip arthroscopy helps in correcting intra-articular impingement, the abnormal biomechanics at the hip due to secondary deformity remains unaltered. Song et al[189] observed that for moderate to severe slips, as slip angle increased, passive hip flexion, hip abduction, and internal rotation in the flexed and extended positions decreased significantly. Persistent pelvic obliquity, medial lateral trunk sway, and trunk obliquity in stance increased, as did extension, adduction, and external rotation during gait. Caskey et al[192] reported improving these biomechanics by flexion rotation osteotomy of the proximal femur. They studied 8 patients who had gait analysis on an average after a year. They found significant improvement in foot progression, internal rotation, and abduction. Other authors have reported correction of this by Imhauser osteotomy.[193–202] They did not address the ongoing intra-articular impingement effect. Therefore, another proposed method of addressing issue of intra-articular impingement and extra-articular deformity was to do corrective intertrochanteric osteotomy and at the same time do a osteochondroplasty.[203–205]

This approach causes a secondary deformity at intertrochanteric level. The above procedure does not eventually negate the need for a total hip arthroplasty. It does improve pain and function in medium to long term, but significant number would then need a total hip arthroplasty after several decades. It would indeed be challenging to correct the proximal femoral deformity for a total hip arthroplasty. Most often a modular prosthesis is needed to put the stem in normal anteversion, neck shaft angle, and normal head shaft offset. This can entail intramedullary reaming through sclerotic bone or re-osteotomising the femur at intertrochanteric level.[206,207] Gallazi et al[207] did a systemic review of patients who had previous femoral osteotomy that subsequently underwent total hip arthroplasty. They reported complications from 0 to 17% and survival of prosthesis from 43.7% to 100% with a follow up of 2 to 20 years.

There are also limitations of complete correction of deformity in severe SCFE with intertrochanteric osteotomy as it is much distal to the centre of rotation of angulation (CORA).[61] Therefore the translations and angulation could be huge which could lessen the contact between the shaft of the femur proximally and distally. Triplane osteotomies at intertrochanteric level involve removal of wedge of bone based, laterally, anteriorly and at the same time rotating the distal shaft internally.[50,133,198] However, none of these osteotomies allude to the fact that there is significant mechanical axis deviation of the lower limb (Fig 1). Ucpunar et al[208] observed in their study of patients pinned in situ at skeletal maturity had lateral deviation of mechanical axis at the knee causing secondary deformity. Therefore, doing further valgus osteotomy at intertrochanteric level will exacerbate the valgus knee deformity and can cause pain or degeneration in the knee. It is well established that with varus intertrochanteric osteotomy one must medialise the distal shaft and with valgus lateralise it (Fig 2). In sagittal plane, flexion osteotomy would require one to move the distal shaft anteriorly (Fig 3). Therefore, there has been significant axis deviation with these osteotomies and its effect on the lower limb has been inadequately studied (Fig 4).[61]

Therefore, the hypothesis was to study the correction of deformity in severe SCFE, to see its outcome and assess complication of AVN with a new approach of surgical dislocation.

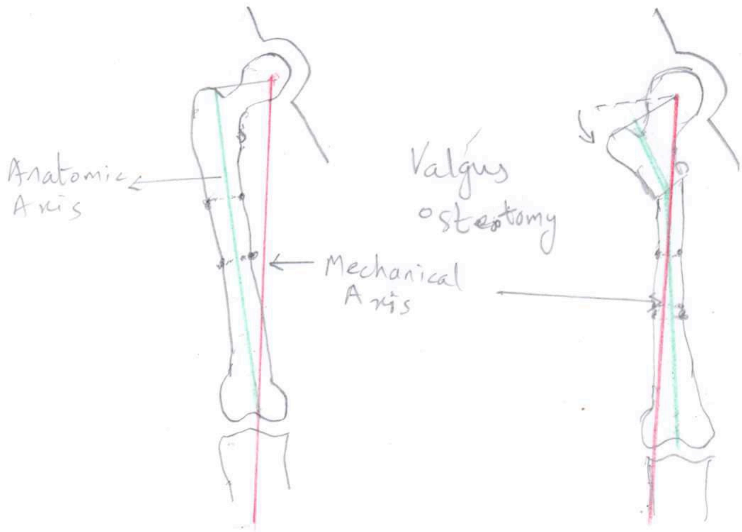


Fig1- Mechanical Axis Deviation (MAD) lateral

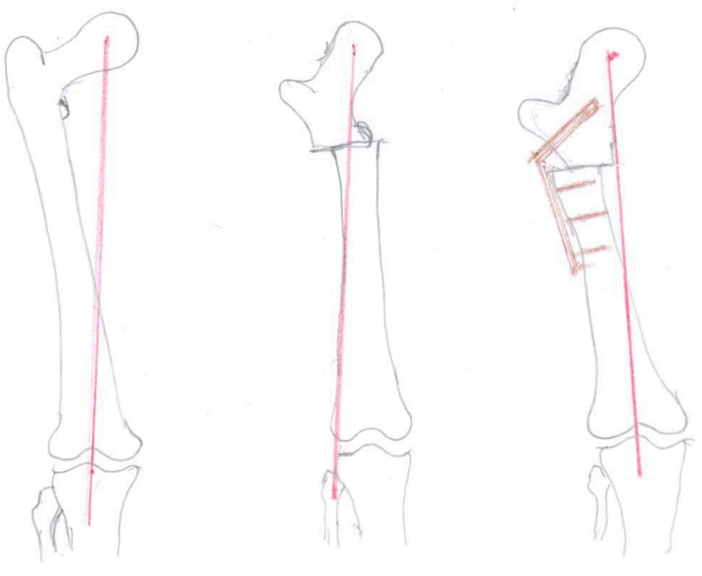


Fig2- MAD restored by lateralisation

Fig. 1. Mechanical axis deviation (MAD) lateral

Fig 2. MAD restored by lateralisation

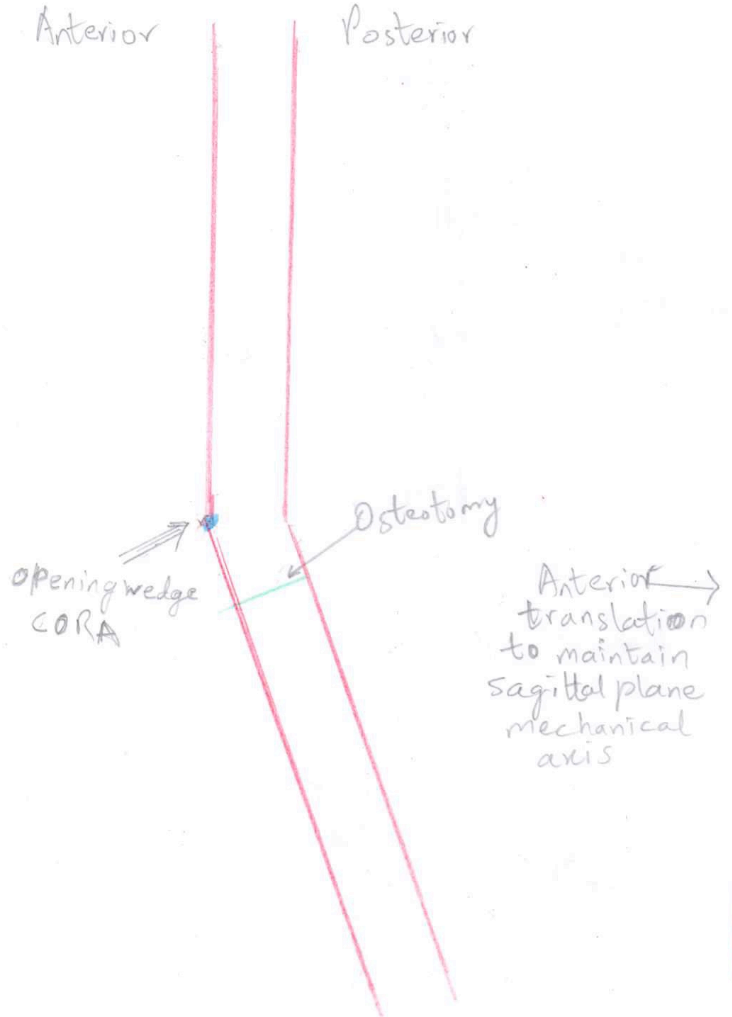


FIG 3. CONCEPT OF ANTERIOR TRANSLATION OF DISTAL SHAFT WHEN FLEXION OSTEOTOMY IS DONE TO CORRECT SAGITTAL PLANE DEFORMITY.
CORA - Centre of Rotation of Angulation

Fig 3. Concept of anterior translation of distal shaft when flexion osteotomy is done to correct sagittal plane deformity.

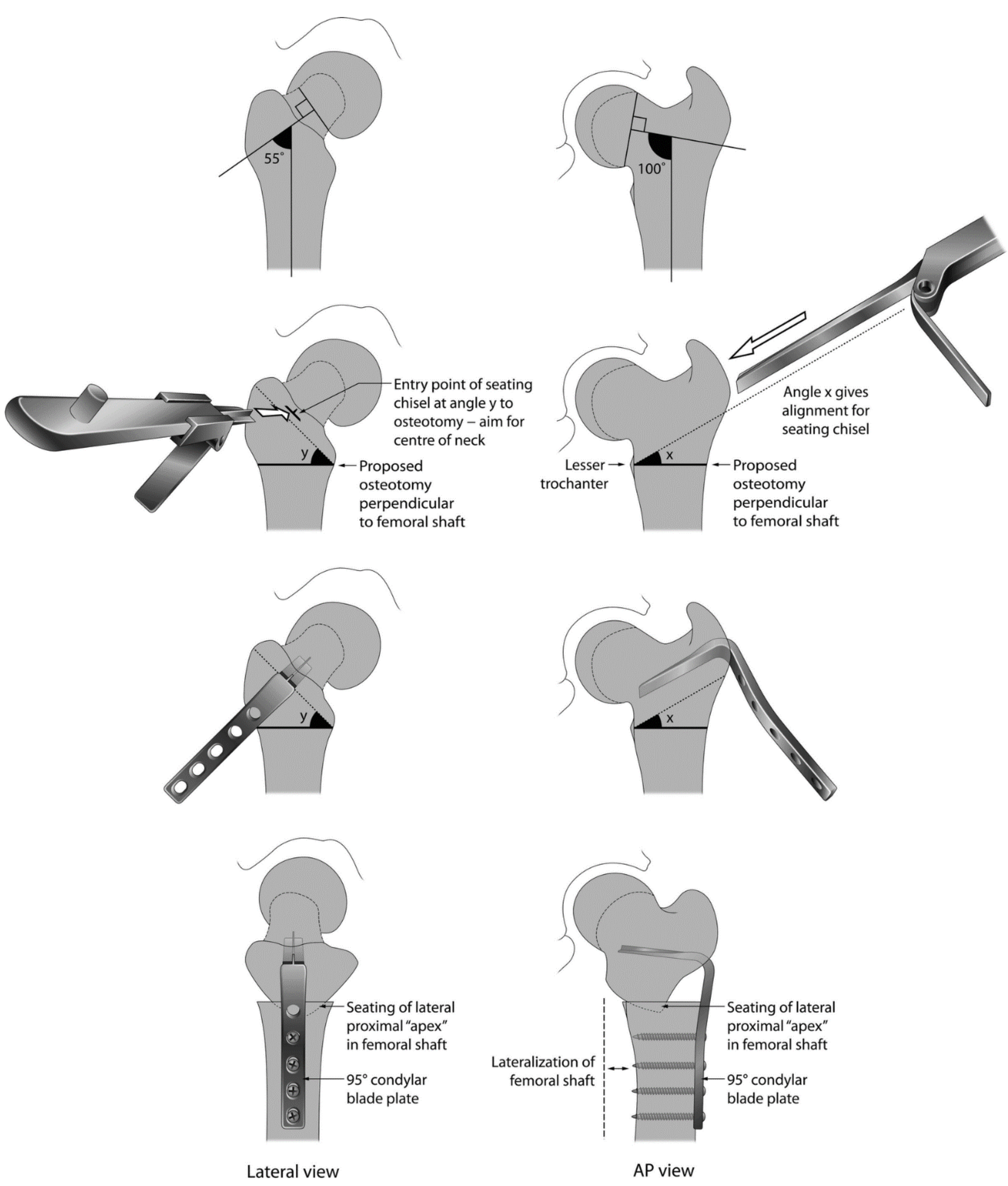


Fig. 4. Correction to show significant translation in all planes.[209]

Our Study

We retrospectively reviewed our hip database from 2006 to 2013 for the diagnosis of slipped capital femoral epiphysis (SCFE) which retrieved 187 cases. Of which 41 patients had undergone surgical dislocation. There was a total of 19 patients with chronic SCFE who underwent surgical dislocation and neck osteotomy or capital realignment. One patient had pre-operative avascular necrosis of the femoral head and was excluded leaving 18 cases for the study. The criterion for inclusion was severe SCFE with minimum 36 months of follow-up.

The study group included patients who had healed severe SCFE managed with in-situ pinning or who presented with problems due to severe deformity of the head and neck without prior treatment.

All the patients were followed up to minimum of 36 months. The radiographs were assessed for anterior slip angle, lateral slip angle, alpha angle and Centre Trochanteric Distance (CTD) in the pre and post-operative films as per the previously described scheme.[50,137,160,210] The deformity in the oblique plane was assessed using the technique described by me (SM).[57]

Subcapital realignment group: (refer to publication 5)

A total of 6 patients underwent capital realignment through the physis.

The neck osteotomy group: (refer to publication 5)

A total of twelve patients underwent anterolateral closing wedge neck osteotomy and fixation after surgical dislocation.

Discussion

Trueta[94] described the changing vascular supply of proximal femoral epiphysis during growth and its vulnerability in SCFE, Perthes and congenital dislocation of hips. This work illustrated subsynovial and intracapsular vascularity rather than the extracapsular course and vascularity of femoral head. He showed that growth plate is a clear barrier preventing the metaphyseal blood from crossing over to the epiphysis. The lateral epiphyseal artery is the predominant blood supply to the capital femoral epiphysis in the preadolescent and early adolescent age. Gautier et al[95] described the extracapsular course of predominant blood supply to the femoral head. The primary source for the blood supply of the head of the femur is the deep branch of the medial femoral circumflex artery (MFCA). They described the anatomy of the MFCA, and its branches based on dissections of 24 cadaver hips after injection of neoprene-latex into the femoral or internal iliac arteries. The course of the deep branch of the MFCA was constant in its extracapsular segment. In all cases there was a trochanteric branch at the proximal border of quadratus femoris spreading on to the lateral aspect of the greater trochanter. This branch marked the level of the tendon of obturator externus, which was crossed posteriorly by the deep branch of the MFCA. As the deep branch travelled superiorly, it crossed anterior to the conjoint tendon of gemellus inferior, obturator internus and gemellus superior. It then perforated the joint capsule at the level of gemellus superior. In its intracapsular segment it ran along the posterosuperior aspect of the neck of the femur dividing into two to four subsynovial retinacular vessels. They demonstrated that obturator externus protected the deep branch of the MFCA from being disrupted or stretched during dislocation of the hip in any direction after serial release of all other soft-tissue attachments of the proximal femur, including a complete circumferential capsulotomy.

Intracapsular transcervical and subcapital osteotomy of the femur has historically been condemned because of high incidence of AVN with that approach.[104,211] At skeletal maturity and beyond there are three sources of blood supply to the femoral head: 1. Intraosseous, metaphyseal nutrient supply from metaphysis to femoral head 2. Retinacular vessels from sleeve of periosteum (lateral epiphyseal artery) and from ligamentum teres, branch of obturator artery.[212–214] The incidence of AVN in undisplaced intracapsular neck of femur fracture varies from 3.4% to 11.8%.[215–217] A undisplaced neck of femur fracture in adults is less likely to disrupt the retinacular blood supply. In same vein we found that after great control in performing subcapital neck osteotomy, we could keep the retinacular vasculature intact and thus we did not have any AVN in 12 cases of severe deformity in skeletally mature patients. The results in literature for subcapital alignment show incidence of AVN from 3% to 29%.[98,104,108,134,137,140,218–220] There were other studies that reported on outcomes of femoral neck osteotomy in healed SCFE.[221,222] Anderson et al[221] reported on 12 cases of healed SCFE and they had two AVNs and one non-union. Bali et al[222] reported on 8 healed cases. They did not have any AVN but reported having 2 non-unions. The subcapital femoral neck osteotomy, has similar AVN risk as subcapital alignment procedure. We propose that transcervical osteotomy should also be an approved procedure because the results are acceptable.

Southwick[50] described a biplane osteotomy at the level of the lesser trochanter to compensate for the deformities caused by a severely slipped epiphysis. He subsequently reported on his experiences with this procedure, documenting the technical difficulties and the high incidence of chondrolysis.[223] These were confirmed by Ogden et al[224] and Salvati et al.[225] This osteotomy, however, cannot correct a slip of more than 70 degrees.[50] The valgus and derotation osteotomy, to align the femoral head and shaft, creates an additional femoral deformity. As a result, the abductor musculature is displaced from its normal position, increasing the muscle force that is necessary to keep the pelvis level.[226] Wedge osteotomy at the base of the femoral neck also does not correct the deformity at the site of the centre of rotation of angulation (CORA), and a maximum correction of only 50 degrees is possible.[227,228,120]

We used Ganz extended retinacular flap technique for both patients with open and closed physis.[229] In my experience raising the retinacular flap was technically far easier in the closed physis group than in the capital realignment group. Bali et al[222] had discussed in their study about the problems with the mobilization of the retinacular flap in chronic slip. They felt that because of the contracture of the soft tissues behind the neck with adhesion to the callus and epiphyseal scar, periosteal mobilization is difficult. This is compounded by the retroversion and varus of the neck. Ganz had mentioned that true neck osteotomy being more often needed at an age when the periosteum is very thin and raising the flap is difficult. He felt that strict subperiosteal exposure with gradual take down of base of greater trochanter to the posterior femoral neck will help to raise the retinacular flap safely.[230]

We conclude that surgical dislocation and careful raising of the retinacular (periosteal) flap safely permits correction of deformity at the CORA avoiding secondary deformity. This will also make future total hip arthroplasty less complicated.

Sample size in this study was small. Complication of avascular necrosis is a major concern in femoral neck osteotomies for chronic healed SCFE. Any such study needs a large sample and be adequately powered to compare it to other methods of correcting deformity. Safety of this method can be adequately assessed in a larger multicenter study for these rare group of patients. Our study could be considered a pilot for designing a proper trial.

Chapter 9: Is Arthroscopy better than osteotomy for severe SCFE after skeletal maturity?

Abstract

Aim: We intend to compare the outcomes of arthroscopic osteoplasty with open neck osteotomy for correction of the hip impingement and improvement of hip function in children with moderate to severe healed Slipped Capital Femoral Epiphysis (SCFE). Our aim is to verify if arthroscopic osteoplasty could achieve the same outcome as open procedures.

Patients and methods: A retrospective analysis of the hospital hip database retrieved 187 cases of SCFE from 2006 to 2013. We found 12 patients underwent open neck osteotomy and deformity correction for moderate/ severe healed SCFE and ten underwent arthroscopic osteoplasty of the hip. We compared the outcomes between these groups.

Results: In the arthroscopy cohort, the mean age at surgery was 15.8 years (range 13–19 years) and mean follow-up was 46.1 months (range 33–66 months). In the neck osteotomy group, the mean age at surgery was 14.6 years (11–20 years) and mean duration of follow-up was 49 months (36–60 months). The outcomes in arthroscopic osteoplasty group vs. open neck osteotomy were as follows: antero-posterior (AP) slip angle 9.2° (0.3°- 28.8°) vs 10.8° (1°–17.9°) ($p = 0.0003$), lateral slip angle 44.8° (36.5°–64.2°) vs 13.5° (1°–28.5°) ($p = 0.00001$), oblique plane deformity 47.1° (40.2°–53.5°) vs 16.7° (1°–28.6°) ($p = 0.0003$), alpha angle 61.88° (52.1°–123°) vs.34.6° (23.2°–45.6°) ($p = 0.0003$), anterior offset 0 mm (0 mm–2 mm) vs. 5 mm (2–13 mm) ($p = 0.0003$), modified Harris hip score (MHHS) 75.5 (58.75–96.8) vs. 90 (86.2–99) ($p = 0.003$), non-arthroplasty hip score (NAHS) 67.12 (18.75–100) vs. 92.1 (81.25–100) ($p = 0.002$), internal rotation 20° (0–20°) vs. 50° (30°–70°) ($p = 0.0002$), respectively.

Conclusion: Even though the radiographic correction lagged in the arthroscopic group, the functional outcomes achieved did convey the gain of function in this cohort. In carefully selected cases, arthroscopy could be a less invasive procedure which has desirable outcomes.

Our hypothesis was that arthroscopy could achieve same outcome as open osteotomy at Centre of Rotation of Angulation (CORA) of deformity for high grade of moderate to severe SCFE.

Remodelling

The current standard treatment for mild to moderate SCFE is by pinning in situ.[36,231] It is argued that there is considerable remodelling potential in SCFE. There have been studies that the remodelling does not completely correct the deformity and femoro-acetabular impingement (FAI) secondary to SCFE can persist. Fraitzl et al[232] reviewed 16 patients with unilateral mild slipped capital femoral epiphysis until after skeletal maturity at a mean follow up of 14.4 years fixed in situ by Kirschner wires. In this study they reviewed these patients for clinical and radiological evidence of femoroacetabular impingement. There was little clinical indication of impingement but radiological evaluation assessing the femoral head-neck ratio and measuring the Nötzli α angle on the anteroposterior and cross-table radiographs showed significant alterations in the proximal femur. None of the affected hips had a normal head-neck ratio and the mean α angle was 86° (55° to 99°) and 55° (40° to 94°) on the anteroposterior and lateral cross-table radiographs, respectively. Jones et al[233] stated that there was good remodelling when the triradiate cartilage was open at time of presentation. They stated that there was potential of 75% remodelling of slips of 40^0 or less in skeletally immature patients. They conclude that there is 50% remodelling in slips greater than 30^0angle. Siegel et al[234] showed remodelling as smoothening effect of the femoral head neck junction which helped in improvement of gait.

Cartilage damage

None of these studies evaluated the potential detrimental effect to the joint cartilage and chondrolabral junction during the remodelling stage. Zilkens et al[235] showed significant joint cartilage damage in 28 subjects at mean age of 23.8 +/- 4.0 years by dGEMRIC MRI scan. Helgesson et al[236] found early osteoarthritic changes in 25 hips at mean age 32 years by dGEMRIC scan. They concluded that damage was worse with increasing severity of slip. SCFE causes silent or asymptomatic FAI that can persist for significant period before patients become symptomatic because of considerable wear to the joint cartilage.[237,238] Murgier et al[239] studied cam FAI in general and found that 43.7% had SUFE type of deformity vs 5.5% in control group. Albers et al[240] found incidence of 112% of SCFE like deformity in primary cam FAI. There are several other studies that show significant mechanical cartilage degeneration because of cam FAI.[241–243]

Gait abnormality

Moderate to severe SCFE can cause external rotation deformity and significant reduction in abduction. This can lead to external foot progression angle and difficulties in sitting because of obligatory external rotation at the hip. Song et al[189] evaluated 30 subjects with treated unilateral slipped capital femoral epiphysis and a range of severity from mild to severe to characterize gait and strength abnormalities using instrumented three-dimensional gait analysis and isokinetic muscle testing. For slip angles less than 30 degrees, kinematic, kinetic, and strength variables were not significantly different from age- and weight-matched controls. For moderate to severe slips, as slip angle increased, passive hip flexion, hip abduction, and internal rotation in the flexed and extended positions decreased significantly. Persistent pelvic obliquity, medial lateral trunk sway, and trunk obliquity in stance increased, as did extension, adduction, and external rotation during gait. Gait velocity and step length decreased with increased amount of time spent in double limb stance. Hip abductor moment, hip extension moment, knee flexion moment, and ankle dorsiflexion moment were all decreased on the involved side. Hip and knee strength also decreased with increasing slip severity. All these changes were present on the affected and to a lesser degree the unaffected side. Body centre of mass translation or pelvic obliquity in mid-stance greater than one standard deviation above normal correlated well with the impression of compensated or uncompensated Trendelenburg gait. Caskey et al[192] concluded that longstanding deformity as a result of a severe SCFE may lead to osteoarthritis of the hip, disabling pain, and functional deficits. Although radiographic evidence of degenerative disease may take years to develop, changes in gait parameters can be immediately evident in this population. A flexion-rotation osteotomy in the adolescent and young adult population can improve gait kinematics, radiographic measures, range of motion, and short-term functional outcome scores. It is felt that normalization of these parameters may reduce the risk of long-term hip deterioration and its related sequelae. Higher grades of severity of slips cause significant biomechanical changes in all the joints of lower limb, tilt in pelvis and could have compensatory changes in spine which can have detrimental effect in stance and posture.[190,244,245]

We wanted to assess whether Arthroscopic osteoplasty was good enough to treat sequelae of SCFE deformity and femoral neck osteotomy could be an overkill.

We retrospectively collected the data from the hospital hip database from 2006 to 2013. There was a total of 187 patients who underwent an operation for a diagnosis of SCFE. Of these, 59 children had moderate or severe SCFE and of these, 12 had undergone open neck osteotomy through surgical dislocation for healed SCFE with a severe deformity. Ten patients with higher grade of moderate and severe deformity had arthroscopic osteoplasty and other intra-articular arthroscopic procedures. These 22 patients formed the study group.

I started doing the arthroscopic osteoplasty for SCFE after I had completed more than 100 hip arthroscopic procedures for various pathologies. The patient and family were offered both the options of open and arthroscopic surgery and given a choice to decide. They were made aware of the limitations of hip arthroscopy in comparison to the open procedure and the relative risk of complications with each procedure. I offered them, in the event of an unsatisfactory outcome with an arthroscopic procedure, a second stage intertrochanteric corrective osteotomy.

Arthroscopic Osteoplasty: In the arthroscopy group, most patients were initially treated with in-situ pinning for moderate and severe SCFE in different centres before referral to our department. They subsequently underwent arthroscopic osteoplasty in our centre. All of them had closed physes.

Procedure

Hip arthroscopy is performed supine on a traction table after hip distraction with standard anterolateral and mid anterior portals. I start the procedure in the central compartment performing capsulotomy to connect the portals, and then do labral-side procedures, like labral repair/debridement, rim trim, cartilage stabilization, and micro-fracture before addressing the cam impingement. The head-neck junction is marked with burr and osteoplasty is performed with 5.5 mm burr. Initial osteoplasty is done with the hip in a neutral position and then in internal and external rotations. The traction is released once the central compartment is fully addressed. The hip is then flexed to 30° and 60° and osteoplasty continued in both external and internal rotations. Later in 10° of extension, the posterosuperior corner is reached to its medial extent to complete the osteoplasty. The whole resection is checked frequently under fluoroscopy throughout the procedure. Pre and post-operative corrections were assessed with the help of the alpha angle, slip angle, antero-posterior (AP) offset and severity of the slip in AP, and lateral and oblique planes.[57] The range of motion of the hip was also recorded before and after the surgery. Clinical signs of impingement and pain were evaluated in the follow-up visits.

Open neck osteotomy: In the open osteotomy cohort, there were patients with and without prior pinning. All patients wanted full functional recovery to return to sports at a level they performed at prior to the slip. They were informed of the risk of AVN and chose to go ahead with the open procedure. These patients underwent open surgical dislocation via the Ganz approach and had an extended retinacular flap dissection after trochanteric flip osteotomy.[246] The neck deformity was corrected by osteotomy at the centre of rotation of angulation (CORA), with realignment and fixation. The details of the correction including the same radiological parameters as described for the arthroscopic cohort were assessed for this patient group. All operations were performed by me using the same technique each patient in both cohorts, thereby eliminating the variability in surgical technique. The groups were compared for the clinical, radiological, and functional outcomes as described. The pre- and post-operative outcome measurements for both the arthroscopy and neck osteotomy groups were computed as mean and standard deviation.

Arthroscopy cohort (refer to publication 6)

There were six girls and four boys in this group of ten.

Neck osteotomy cohort (refer to publication 6)

There were six boys and six girls in the open neck osteotomy group.

Comparing the two groups showed that the open neck osteotomy had significantly better results (Table 1). The range of motion data in both groups are shown in Table 2.

Table 1. Comparison of outcomes between the groups.

	Neck Osteotomy (N=12)	Arthroscopy Osteoplasty (N=10)	P value
AP slip angle	10.8^0 (1^0-17.9^0)	9.2^0 (0.3^0 – 28.8^0)	0.0003
Lateral slip angle	13.5^0 (1^0-28.5^0)	44.8^0 (36.5^0-64.2^0)	0.00001
Oblique plane deformity	16.7^0(1^0-28.6^0)	47.1^0(40.2^0-53.5^0)	0.0003
Alpha angle	34.6^0(23.2^0-45.6^0)	61.88^0(52.1^0-123^0)	0.0003
Anterior offset	5 mm (2-13 mm)	0 mm (0-2 mm)	0.0003
MHSS	90 (86.2-99)	75.5 (58.75-96.8)	0.003
NAHS	92.1(81.25-100)	67.12 (18.75-100)	0.002
Internal rotation	50^0 (30^0-70^0)	20^0(0-20^0)	0.0002

Table 2. Mean range of motion (^{0}).

Group	Flexion		Abduction		Adduction		Internal rotation		External rotation	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post

Osteotomy	80	120	30	45	20	30	0	50	50	50
Arthroscopy	75	97	20	35	20	30	0	20	45	50

<u>Discussion</u>

Osteotomy in the proximal femur is a powerful way to correct the deformity that happens at the growth plate. Various osteotomies have been described in literature to address this.

Southwick[50] (Fig. 1) described lateral and anterior based wedge intertrochanteric osteotomy that corrects the varus and extension deformity. One could derotate the shaft to improve the external rotation deformity at the same time.

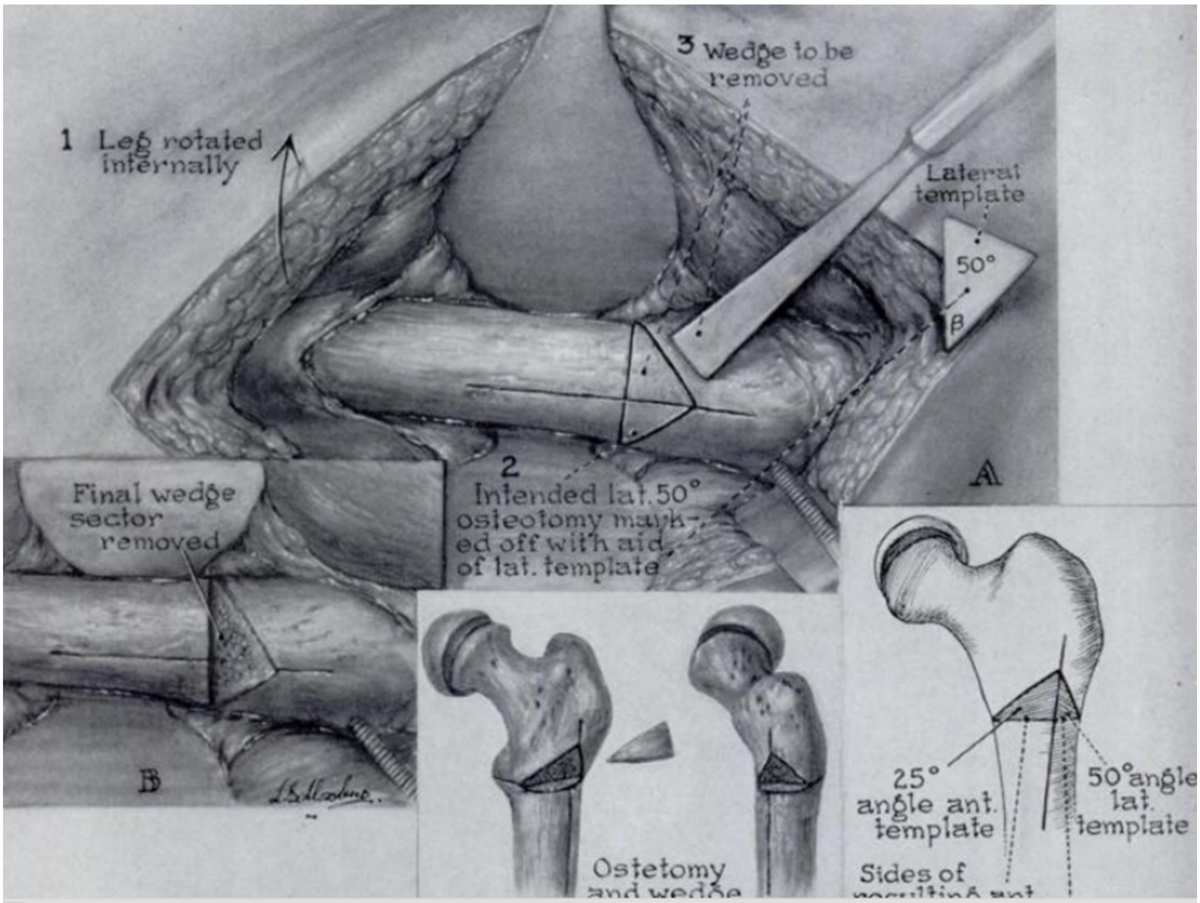


Fig. 1 Southwick Osteotomy

Mamisch et al[247] demonstrated with computer simulation of range of motion (ROM) before and after uniplanar and multiplanar intertrochanteric osteotomy. There was inadequate correction of impingement and retroversion. They proposed correction of impingement by osteoplasty and rotational osteotomy of femur at intertrochanteric level. Griffith described a geometric flexion osteotomy to correct the deformity.[133]

Imhauser osteotomy is a triplane osteotomy at the intertrochanteric level that tries to address the SCFE deformity.[193,198,199,202] Such triplane intertrochanteric osteotomies create another deformity at intertrochanteric level and leave the intracapsular neck deformity uncorrected. To address this issue several authors studied the combined approach of intertrochanteric osteotomy with intracapsular osteoplasty to rectify FAI.[203–205,248] Although they claimed that the results were gratifying, its effect on prevention or delaying of OA has never been conclusively proven. Some patients with these deformities will need total hip arthroplasty, and this then becomes a complex procedure because of previous intertrochanteric osteotomy. There are other biplane and triplane intertrochanteric and subtrochanteric osteotomies with similar issues.[199,249–252] To have minimal effect on the proximal femoral deformity Kramer et al proposed a basicervical femoral osteotomy.[253] Although this is somewhat protective of blood supply to femoral head, it suffers the same disadvantage of persistence FAI.

Therefore several authors proposed a transcervical or subcapital femoral osteotomy to correct the deformity and also impingement at the site of angular deformity.[108,246,254–258] However there is risk of avascular necrosis with capital realignment for chronic severe slip. Broughton et al[134] found in 70 hips with a chronic slip and an open growth plate the incidence of complications was low: two developed avascular necrosis, five chondrolysis, and one had both. Alshryda et al[255] showed an AVN rate of 6.9% with Fish cuneiform osteotomy. Clarke and Wilkinson[256] had 17.4% AVN in their chronic moderate to severe slip treated with cervical osteotomy. Barros et al[257] reported AVN in 3 of their 20 patients with chronic slip treated with trapezoidal femoral neck osteotomy. Gage et al[259] reported 28.5% AVN in chronic slip with subcapital or femoral neck wedge osteotomy. Sikora-Klak et al[218] had 29% AVN in the 14 moderate and severe stable SCFE treated by modified Dunn procedure.

It gets even more controversial when one must do cervical osteotomy in a healed deformed SCFE. Anderson et al[221] reported on 12 cases of healed SCFE and they had two AVNs (17%) and one non-union. Bali et al[222] reported on 8 healed cases. They did not have any AVN but reported having 2 non-unions. The subcapital femoral neck osteotomy, has similar AVN risk as subcapital alignment procedure. We did not have AVN but had one non-union and conclude that cervical femoral neck osteotomy is a reasonable procedure for surgeons experienced in modified Dunn procedure. I have discussed this issue in the chapter of neck osteotomy for SCFE.

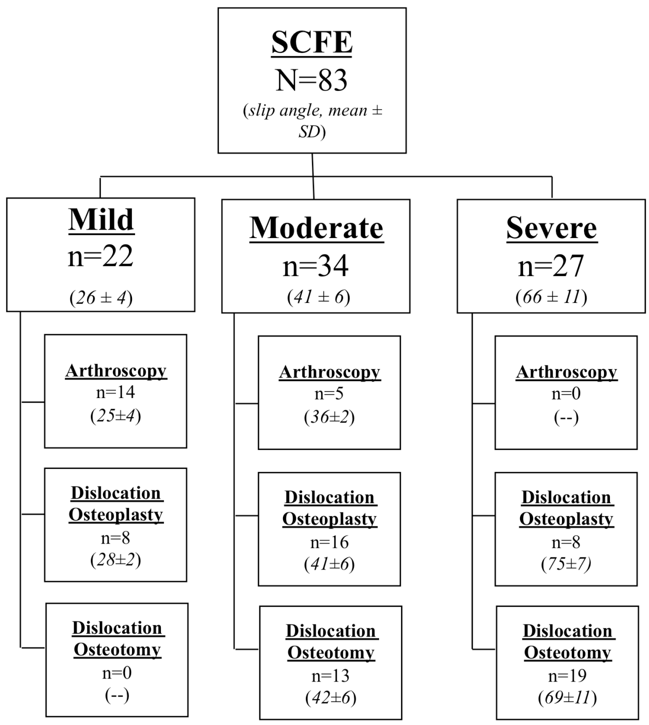
Following table compares our study from 2015 to the other studies:

	Anderson et al[221]	Bali et al[222]	Our study
Number of hips	12	8	12
Mean age	15 (12-19)	17.8 (13-29)	14 (11-20)
Gender (M/F)	7/4	6/2	6/6
Prior pinning in situ	9	8	8
Timing from pinning to osteotomy- months	29(4-73)	42 (12-144)	14.6 (11-16)
Mean follow-up - months	61 (6-104)	41 (20-84)	48(36-60)
AVN	2/12	0/8	0/12
Non-union	1/12	2/8	1/12
Apha pre	85 (77.1 to 92.4)	64 (50 to 78)	81.6 (62.5 to 99)
Alpha post	46 (41.9 to 49.8)	32 (25 to 39)	34.65 (23.2 to 45.6)
mHHS	77 (64.1 to 89.6)	92.5 (85 to 100)	91.4 (86.2 to 100)

Most papers in literature have shown satisfactory outcome in correction of FAI in mild SCFE with arthroscopy.[260–262] There are only few series that describe patients with moderate and severe grade SCFE treated with arthroscopy. Chen et al[263] reported on arthroscopic osteoplasty for 21 mild, 16 moderate and three severe grades of SCFE. At minimum 1 year follow up, complete resolution of pain and correction of obligatory external rotation was obtained in 88% of patients. Wylie et al[264] reported on six mild and three moderate SCFE treated with arthroscopy. The alpha angle improved from 75° preoperatively to 46° postoperatively. The mean follow-up period was 28.6 months (range, 12.6 to 55.6 months). The mean modified Harris Hip Score improved from 63.6 preoperatively to 91.4 postoperatively. Basheer et al[160] (SSM senior author)reported on 18 patients with a mean age of 19 years (13 to 42), presenting with pain in the hip and mechanical symptoms, and had evidence of FAI (cam or mixed impingement) on plain radiographs. The patients underwent arthroscopic osteoplasty of the femoral neck. The mean follow-up was 29 months (23 to 56). The mean mHHS and NAHS scores improved from 56.2 (27.5 to 100.1) and 52.1 (12.5 to 97.5) pre-operatively to 75.1 (33.8 to 96.8, $p = 0.01$) and 73.6 (18.8 to 100, $p = 0.02$) at final follow-up, respectively. Linear regression analysis demonstrated a significant association between poorer outcome scores and increased time to surgery following SCFE ($p < 0.05$ for all parameters except baseline MHHS). They concluded that symptomatic FAI following SCFE may be addressed using arthroscopic techniques and should be treated promptly to minimise progressive functional impairment and chondrolabral degeneration. There were 5 patients with severe SCFE in this group.

In our paper Balakumar et al[265] compared outcomes of arthroscopy osteoplasty to open subcapital femoral osteotomy in healed SCFE. We had 10 patients in arthroscopic group of which 7 were severe and the moderate group was between 47 to 50 degrees oblique plane slip angles.[57] The osteotomy group comprising of 12 hips were all severe grade. We did show that osteotomy group had much greater improvement in functional scores. However, patients were equally satisfied with their outcomes in both groups. Patients in arthroscopy group were told that as a second stage they could have femoral rotational osteotomy. None of the patients wanted it as they were satisfied with the outcome, because they had good improvement in obligatory external rotation and could sit and walk better with normal or near normal foot progression angle.

Wylie et al[266] compared arthroscopic treatment to intertrochanteric osteotomy group with and without osteochondroplasty. Their group was skewed because the majority of patients in arthroscopic group had milder SCFE. They did show improvement in all groups as shown below:



We conclude that arthroscopy is a low-risk option to treat moderate to severe SCFE with no risk of AVN and a low complication outcome.

Chapter 10: Limitations

My studies included for this thesis are case series. However, the cohort of patients had new interventions and their clinical and radiological evaluation was done and compared to the literature. However, the end point in these studies was avascular necrosis. This determined the survivorship of the hips. With this end point in mind these case series, in my studies, have merit in informing readers the value of doing these procedures.

These studies had patient selection bias. I chose to do one procedure over another because of my personal preference and the skill set that I had acquired. For instance, I chose to do femoral neck osteotomy or subcapital realignment in more severe deformities and lesser severe cases did arthroscopy. These cases weren't randomised, and this is a significant limitation.

Outcome measures chosen were not necessarily validated in these group of patients. I also used clinical scores which have inherent limitations. Modified Harris hip score (mHHS) is applicable for arthritic patients. Non arthritic hip score (NAHS) doesn't capture quality of life data. We did not use a quality of life score like EQ-5D-Y[267,268] . Luo et al[269] (2021) have assessed the validity of PROMIS Mobility score as outcome measure tool for hip disease in adolescents for aged >/= 12 years. They compared this to NAHS, and they found good correlation. Other authors have shown PROMIS to be a good outcome measure.[270–276] However, it failed to pick up certain important elements of hip disease. At the time of our study there were no reliable, validated outcome measures for our group of patients. We had to use surrogate measures such as NAHS or mHHS in our study. Our results therefore should be interpreted with this shortcoming.

Lack of control group was another limitation of our study. We did not compare our method of say surgical dislocation technique to another approach for these group of patients. For instance, we had no control group in our arthroscopy or femoral neck osteotomy study. Having controls makes study robust and gives a feel of effect size for a method of treatment under study. Our results must be interpreted with its limitation.

These studies weren't validated. We did not compare our studies to a gold standard. This was a major limitation. The novel method of classification was assessed for reliability. We did not validate the displacement of epiphysis measured in this classification with observed displacement intra-operatively. Neither did we compare this to standard like Southwick method of classification. Similarly, our method of salvaging AVN hips, treatment with arthroscopy, femoral neck osteotomy and surgical dislocation technique weren't compared to another well-established method of treatment. This limitation must be taken into consideration in interpreting our results.

However, we maintained consistency in the papers by using modified Harris Hip score and Non-arthritic Hip Score throughout all relevant papers submitted for this thesis.

Future Work

These 6 studies could help us to design future larger clinical trials.

1. Novel classification: We could validate this classification by intra-operatively measuring the magnitude and direction of displacement of capital femoral epiphysis, and by comparing it prospectively using Southwick's method of classification, using 3D reconstructed CT scan for displacement. We can also use 3d printer to measure the magnitude and direction of slip to validate this classification.
2. Open reduction of SCFE: One could design a multicentred study to compare different methods of open reduction for severe grade of unstable and stable slips. This would be a pragmatic study and we could then assess the outcomes and complications.
3. Avascular necrosis: We have proposed a method of treating avascular necrosis for unstable SUFE. We could design a multicentred study and compare various methods of treating and salvaging these hips. For instance, we could do gentle close reduction, assess the vascularity with SPECT or perfusion MRI scan and do hinged distraction. This could be one arm of the study. We could also have another arm of the study by using Bisphosphonates. To study these variables, we will need a multicentre study with large numbers. We could run a multicentre feasibility study to estimate the effect size. This will help us to calculate the sample size for our cohort.
4. Arthroscopy: We could design a prospective longitudinal study to treat symptomatic secondary FAI by arthroscopy vs open surgery as a one comparative study. Another arm would be arthroscopy vs open osteochondroplasty with intertrochanteric osteotomy to correct the deformity. As explained above this would also need to be multicentre study.
5. Femoral neck osteotomy: A study comparing this to traditional intertrochanteric osteotomy could be a good study to assess outcomes and complications.

We could prospectively use certain validated scores such as EQ-5YD or PROMIS mobility scores to assess these group of patients effectively.

Somme other future relevant work would be to do feasibility studies and get effect size and then get grants for multicentre NIHR studies for RCTs for

1. Pinning in situ vs Pinning in situ and arthroscopy at same sitting for mild and moderate SCFE
2. Gentle closed reduction vs open reduction for unstable SCFE irrespective of timing of presentation
3. Arthroscopy vs subcapital femoral osteotomy for healed severe SCFE.
4. Subcapital femoral osteotomy or realignment vs intertrochanteric/ subtrochanteric osteotomy with osteochondroplasty to correct FAI.

Chapter 11: Conclusion

In this thesis, I have endeavoured to illustrate my approach to the various vexed problems in SCFE. I proposed a new classification so that one could plan for the surgery. This would then enable a surgeon to treat mild to moderate SCFE with pinning in situ and then maybe in some symptomatic cases, do a second stage arthroscopy to correct FAI. In case of severe SCFE, surgeon would be well equipped to proceed with their choice of open surgery, although one of the best approaches for anatomical reduction could be by Ganz's modification of Dunn's surgical procedure. This would also be one of the best approaches to treat unstable slip. As a continuum of this treatment, I proposed a salvage procedure for AVN of the femoral heads. I also argue that to correct severe deformity, subcapital femoral osteotomy is a reasonable procedure to correct the deformity.

My journey has continued since these publications to improve my outcomes. I have, in our centre, been able to diagnose with reasonable accuracy AVN of proximal femoral epiphysis for unstable slip before we embark on any treatment by using perfusion MRI scan. This study is unique because it will tell the surgeon, the true incidence of surgical morbidity. This is the first time in history that this has been done. This study was awarded the best paper at British Society of Children's Orthopaedic Surgery in 2021. I will continue this path to explore and manage challenging issues in SCFE. As my journey continues, I may find that some of my solutions maybe short lived and some may not be as rewarding in the long term. Only time will tell.

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Appendix 1

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ISSN (print): 1863-2521 | ISSN (online): 1863-2548

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Appendix 3

Related papers read regarding the techniques used to treat SCFE

PODIUM

S S Madan, S Bajaj, R Maheshwari, L Regan. *Hip Arthroscopy. EPOS, April, 2010.*

S Bajaj, R Maheshwari, S Jones, J A Fernandes, S S Madan. *Surgical dislocation for correction of severe pistol grip deformity of SUFE. EPOS, April, 2010.*

S S Madan, R Maheshwari, S Jones, J A Fernandes. *Surgical dislocation and anatomical reduction of severe SUFE, BSCOS, Birmingham, UK, 2009.*

M Padman, J A Fernandes, S Jones, S S Madan. *When does a mild SUFE present as severe deformity?BSCOS, Birmingham, UK, 2009.*

D S Feldman, S Madan, W B Lehman. *Articulated hip distraction arthroplasty for AVN and chondrolysis. Paper read at ASAMI, Dallas, Texas, 2002.*

R Kucharski, R Mahaeshwari, S Madan. *Surgical dislocation and anatomical reduction of severe slipped upper femoral epiphysis. EPOS, Lisbon, 2009.*

R Maheshwari, A Sabboubeh, S S Madan. *Outcomes of hip arthroscopy using two portal technique for central and peripheral compartment. Vienna, EFORT 2009*

Appendix 4

Co-author permissions

Dear Balakumar

I am currently in the process of applying for a PhD by publication at the University of Sheffield (Slipped Capital Femoral Epiphysis: Evaluation of Novel Surgical Approaches for Difficult Problems). As a co-author on the papers listed below, I would be grateful if you would allow me to include these papers in my submission. If you agree to this, could you please sign this document and return to me by email: s.madan@sheffield.ac.uk or by post to

Mr Sanjeev Madan, Consultant Orthopaedic Surgeon, Sheffield Children's Hospital, 12 Northumberland Road, Broomhall, Sheffield S10 2TT.

Kind Regards

Sanjeev Madan

List of co-authored papers

Basheer SZ, Cooper AP, Maheshwari R, Balakumar B, Madan S. Arthroscopic treatment of femoroacetabular impingement following slipped capital femoral epiphysis. *Bone Jt J*. 2016;98-B(1):21-27. doi:10.1302/0301-620X.98B1.35831

Balakumar B, Madan S. Avascular necrosis post unstable slipped capital femoral epiphysis: a treatment algorithm with staged hinged hip distraction: mid-term results. *Hip Int*. 2019;29(4):438-445. doi:10.1177/1120700018811313

Balakumar B, Flatt E, Madan S. Moderate and severe SCFE (Slipped Capital Femoral Epiphysis) arthroscopic osteoplasty vs open neck osteotomy-a retrospective analysis of results. *Int Orthop*. 2019;43(10):2375-2382. doi:10.1007/s00264-018-4069-6

Balakumar B, Madan S. Late correction of neck deformity in healed severe slipped capital femoral epiphysis: short-term clinical outcomes. *Hip Int J Clin Exp Res Hip Pathol Ther*. 2016;26(4):344-349. doi:10.5301/hipint.5000347

I agree to the inclusion of the above listed published research article in Mr Sanjeev Madan's PhD by publication thesis, to be submitted to the University of Sheffield.

Name: B Balakumar

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Date: 14/08/2021

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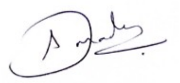

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Basheer SZ, Cooper AP, Maheshwari R, Balakumar B, Madan S. Arthroscopic treatment of femoroacetabular impingement following slipped capital femoral epiphysis. *Bone Jt J*. 2016;98-B(1):21-27. doi:10.1302/0301-620X.98B1.35831

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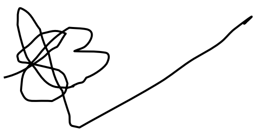
Signed: 

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Dear Geraint

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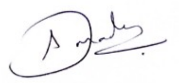

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List of co-authored papers

Madan SS, Cooper AP, Davies AG, Fernandes JA. The treatment of severe slipped capital femoral epiphysis via the Ganz surgical dislocation and anatomical reduction: a prospective study. *Bone Jt J*. 2013;95-B(3):424-429. doi:10.1302/0301-620X.95B3.30113

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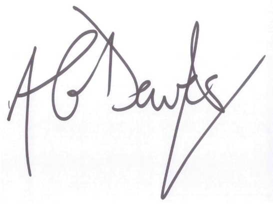
Name: A G Davies

Signed:



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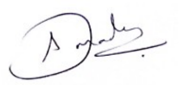

Sanjeev Madan

List of co-authored papers

Cooper AP, Salih S, Geddis C, Foster P, Fernandes JA, Madan SS. The oblique plane deformity in slipped capital femoral epiphysis. *J Child Orthop*. 2014;8(2):121-127. doi:10.1007/s11832-014-0559-2

Madan SS, Cooper AP, Davies AG, Fernandes JA. The treatment of severe slipped capital femoral epiphysis via the Ganz surgical dislocation and anatomical reduction: a prospective study. *Bone Jt J*. 2013;95-B(3):424-429. doi:10.1302/0301-620X.95B3.30113

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Name: James A Fernandes

Signed:

Date:10/08/21

Dear Ellie

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Kind Regards

Sanjeev Madan

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Balakumar B, Flatt E, Madan S. Moderate and severe SCFE (Slipped Capital Femoral Epiphysis) arthroscopic osteoplasty vs open neck osteotomy-a retrospective analysis of results. *Int Orthop*. 2019;43(10):2375-2382. doi:10.1007/s00264-018-4069-6

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Name: E Flatt

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Dear Carolyn

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Kind Regards

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Name: Carolyn Geddis

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Date: 14.8.21