Complications in children's orthopaedics: avoiding late deformity in paediatric fracture surgery

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Abstract

Paediatric orthopaedic surgery can be an unfamiliar and challenging field with the potential for devastating consequences. This article discusses late deformity associated with humeral supracondylar fractures and slipped capital femoral epiphysis (SCFE). Common complications include loss of fixation, mal-reduction, avascular necrosis and growth disturbance. Many cases result in reoperation and revision surgery associated with significant morbidity. We discuss the risk factors, aetiology, tips to avoid them and management options based on current evidence.

Keywords avascular necrosis; deformity; mal-reduction; paediatric; slipped upper femoral epiphysis; supracondylar fracture

Humeral supracondylar fracture

Supracondylar (SC) fractures of the humerus represent 50–70% of elbow injuries in children.[1,2] Acute management of the displaced SC fracture is often technically challenging and can be the source of much anxiety, even for experienced orthopaedic surgeons. Recently there has been an increasing trend in the UK and more widely toward centralization of services and tertiary referral for most displaced Gartland grade 3 SC fractures.[3]

Despite SC fractures representing one of the most commonly treated fractures in children, surgical experience during the training of orthopaedic and trauma surgeons is often limited. In a survey of 121 UK paediatric orthopaedic consultants, 69% felt that the management of Gartland 3 SC fractures should be a consultant-delivered procedure.[4] UK training has recently been updated to include the performance of five paediatric SC fracture fixations as essential (indicative) procedures required for gaining a completion of certificate of training. Recently published studies have reported learning curves of between 15 and 20 fixations with the need to perform a further five per year to maintain proficiency and reduce the rates of complications[4]

Pesenti[5] and colleagues demonstrated that both experience and volume are important factors determining the quality and outcome of surgically treated SC fractures. The authors reviewed radiographic and operative results of 236 children over an 11-year period. A 12% rate of mal-alignment in the immediate postoperative period was identified which dropped to 7.6% after remodelling potential had been reached. Authors noted a trend toward decreasing rates of mal-alignment with increasing number of cases performed, with rates plateauing after 20 cases. For surgeons treating fewer than five cases/year there were higher intraoperative rates of conversion to open reduction (45% vs 22%) and significantly higher rates of late mal-alignment (16% vs 8%).

Liu et al. also supported these findings, noting significant differences in the rate of non-ideal intraoperative reduction and loss of fixation for fellows (13%) compared with that of experienced attending surgeons (4%). Learning curve plots identified a steep increase in the rate of non-ideal reductions at case 7, which was largely attributed to fellows moving towards a more independent practice and a trend reversal after 15 cases to reach a stable plateau. The authors concluded that the availability of a backup-attending surgeon is advisable during the first 15 cases[5]

This raises the controversial issue of whether the average 'day 1 consultant' is appropriately equipped to treat a difficult Gartland 3 SC fracture and what tips and tricks can be identified to alleviate anxiety and prevent complications.

Successful treatment of these injuries depends on growth prognosis, with complete fracture remodelling and physeal arrest representing opposite ends of the spectrum of possible outcomes. The risk of growth arrest around the elbow with SC fractures is low, however the potential for spontaneous remodelling is also low and cannot be relied upon, even in younger children[1,6]

The majority (approximately 65%) of the longitudinal growth of the humerus is complete by the age of 6 and only 20% of any remaining growth occurs in the distal humerus.[15] As a result even small amounts of displacement require closed reduction (CR) percutaneous pinning.[1]

Common deformities following SC fracture include hyperextension and cubitus varus. In children, true loss of flexion after supracondylar fracture is rarely due to scarring or stiffness and must be carefully assessed for a sagittal plane deformity, typically an extension mal-union.[7]

Paradi[8] et al. concluded that the return of elbow function is dependent primarily on the quality and maintenance of the initial reduction. Similarly Kepler[9] and colleagues supported this, and demonstrated no requirement for physiotherapy postoperatively and consistently good outcomes in well-reduced fractures.

Cubitus varus has been attributed to mal-reduction, loss of fixation and occasionally partial growth arrest of the medial condylar physis.[10,11] In most cases it is a largely cosmetic complaint due to a prominent lateral epicondyle, distal humeral internal rotation and subsequent 'gunstock' deformity.

However, changes to the biomechanical forces around the elbow joint can cause medial displacement of the mechanical

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axis, increased tensile forces across the lateral collateral ligament complex and late attenuation. In severe deformities triceps may also be medially displaced causing a resultant supination force vector across the ulna. These can cause resultant tardy ulnar nerve palsy, anterior dislocation or subluxation of the ulnar nerve, posterolateral rotatory elbow instability, medial head triceps shift with snapping, posterior shoulder instability with a Bankart lesion and increased risk of lateral condyle fractures.[8,12]

Symptomatic cubitus varus may necessitate treatment with late corrective osteotomy[7] to address both the angular and rotational components of the deformity. Common techniques include dome, bi-planar or lateral closing wedge osteotomies to de-rotate and medialize the distal fragment.[8]

In order to avoid late complications and need for deformity correction, anatomical intraoperative reduction and fixation sufficient to maintain the reduction are essential. Reports of mal-reduction at the time of surgery currently range from 13% to 32% and rates of inadequate fixation range from 14% to 42% depending on the experience of the surgeon.[13]

Intraoperative technique and predicting loss of fixation

The distal humerus has limited remodelling potential; surgeons should aim to achieve acceptable reduction with minimal deformity that is stable after wiring.[7] Baumann's angle is frequently quoted as an important primary outcome measure in the assessment of SC fractures. However it is clinically difficult to use as an intraoperative marker of reduction and immediate follow-up. Baumann's angle cannot be accurately measured with the elbow in a flexed position and therefore its role in assessment and decision-making regarding intraoperative quality of reduction and postoperative maintenance of reduction is limited.

Most published literature on deformity after fixation focuses on growth and remodelling for coronal plane mal-alignment. There is, however, little published as to the acceptable limits of sagittal plane deformity.[14] In younger children (<3 years) an anterior line touching the capitellum is likely to remodel. However in children older than 8 years only 10% of growth remains. In cases of isolated extension, a shaft condylar axis angle of more than 15° is thought to warrant intervention.[37] Persistent extension or translation of the distal fragment that is not addressed can cause anterior impingement, reduced elbow flexion and loss of function[15]

Simanovsky[15] et al. reported inadequate reduction of sagittal plane deformity in 13.5% of SC fractures. At skeletal maturity 77% of this cohort had residual radiographic abnormality of the ulnohumeral angle of more than 5° compared with the uninjured limb, 50% had limitation of elbow flexion and 14% considered it functionally disabling. A strong correlation between post-reduction ulnohumeral angle and limited elbow flexion at skeletal maturity was noted.

Extension fractures account for between 97% and 99% % of all SC fractures.[8] CR is a well-recognized technique with high rates of success. In significantly displaced fractures the proximal fragment occasionally buttonholes through the brachialis muscles. This clinically presents with medial bruising and skin puckering. The 'pucker sign' is a marker of injury severity, is associated with significant displacement, increased likelihood of multidirectional instability, increased rates of brachial artery or median nerve involvement and possible need for progression to open reduction.[15] Prior to CR the proximal fragment must be reduced through brachialis using the 'milking manoeuvre'.[8]

Principles of CR involve traction with counter-traction to disimpact the fracture and allow manipulation. The coronal plane displacement is corrected shifting the distal fragment medial or lateral as the fracture dictates. Rotational deformity may respond to supination or pronation of the forearm. Finally the sagittal plane deformity is reduced with flexion of the elbow whilst providing pressure to the olecranon. We recommend that the surgeon continues to apply traction with one hand, while the other hand is used to apply a flexion force to the olecranon with a thumb and the fingers opposing this force on the anterior aspect of the humerus. Other indirect reduction techniques have been described, such as passing Kirschner wires (K wires) into the distal fragment as joysticks,[16,17] which may be useful in cases of multidirectional instability. A Kapanji-style posterior intrafocal K wire has also been described although this relies on a intact posterior periosteal hinge and therefore has limited use in our opinion[8,18,19]

Open reduction may be necessitated in cases of unsuccessful CR, concerns regarding neurovascular compromise or soft tissue entrapment. The pulse should always be checked after reduction to ensure the brachial artery is not in the fracture site.

Mal-reduction is common and often either underappreciated intraoperatively or not recognized in the early postoperative period. Obtaining a true lateral radiograph at follow-up may be challenging. It is our practice to ensure oblique or 'almost' lateral intraoperative images are saved to allow easier comparison in the postoperative setting.

A number of radiographic measures have been reported to assess intraoperative reduction as follows.

1. Anterior humeral line or Roger's line: failure to pass through the middle third of the capitellum suggests persistent extension deformity.
2. Shaft condylar angle: an angle formed on lateral radiograph between the long axis of the humerus and long axis of the lateral condyle with a normative value of 40°.
3. Lateral teardrop: this represents the margin of the coronoid fossa, anterior margin of the olecranon fossa and superior border of the ossification centre of the capitellum.
4. Coronoid line: on the lateral radiograph a line drawn along the anterior border of the coronoid process of the ulna should touch the anterior part of the lateral condyle of the humerus. If the lateral condyle appears posterior to this line, posterior displacement is present.
5. Baumann's angle (also known as the 'shaft physeal' line) is measured on the anteroposterior (AP) radiograph. A line is drawn parallel to humeral shaft and parallel to the angle of the lateral physis. It has a broad range of normal values ranging from 64° to 82° or within 5° of the contralateral side.
6. Persistence of an anterior cortex gap or ventral spur on the lateral view suggests possible neurovascular, soft tissue interposition or persistent rotational mal-reduction.
7. Ulnohumeral angle or radiological carrying angle: on an AP view the angle is formed by the diaphyseal axis of the humerus and the ulna. The normal physiological carrying angle

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is 5–15° valgus. A decreased angle is associated with cubitus varus.

Careful consideration should be given to the direction of displacement, varus or valgus angulation, extent and location of fracture comminution and the Baumann's angle, which varies greatly with rotation.[20] The distal humerus at this level is a flat bone and as such any malrotation vastly reduces the contact surfaces available for initial stability and bony healing.

In addition to achieving adequate intraoperative reduction, technically proficient wiring is key to avoid complications (Figures 1 and 2).

Balakumar and Madhuri[21] reported a close correlation between loss of fixation and unaddressed technical errors during surgery. In cases with inadequate intraoperative fixation they reported 38.9% loss of reduction at 3 weeks compared with 0% in cases with technically sound fixation. Common technical errors were lack of purchase in either the distal or proximal fragment and inadequate wire spread. No significant differences were identified based on the stability of fracture configuration. Authors noted that in cases of an imperfect reduction a technically sound pinning could avert a major loss of reduction.

Optimum wire configuration and stability remains an area of controversy. There is little evidence in the literature to demonstrate superiority of one particular wiring technique. Common techniques include two or three crossed wires or two or three lateral wires. Medial and lateral wiring techniques have inherently different risk profiles and selection is often dependent on surgeon experience and fracture morphology.

Lateral wiring techniques may be more technically challenging. A recent prospective randomized control trial (RCT) of surgeons in their first 3 years of training demonstrated a significantly lower loss of fixation when using crossed (0%) versus lateral wiring techniques (20%), with no significant difference in iatrogenic nerve injury.[38] Lateral wiring relies on solid fixation in the capitellum ossification centre and the humeral cortex proximal to the fracture. Common causes of failure in lateral wiring include: a posterior entry point missing the ossification centre and hence having fixation in cartilage not bone, poor divergence of the wires allowing the distal fragment to slide on the wires and use of lateral wiring in inappropriate fracture configurations.

A large meta-analysis of RCTs and prospective comparison cohorts reviewed a 14-year period, including 1158 children with SC fracture comparing crossed and lateral wire configuration demonstrated no difference in loss of reduction when using crossed (11.6%) or lateral wires (12.4%).[22] This is supported by a further meta-analysis of 1615 children, which showed similar rates of revision surgery for loss of fixation in standard crossed (1.3%) and lateral constructs (2.1%) with no difference in long-term outcomes of late deformity or poor function but a 4.3 times higher rate of iatrogenic nerve injury when a medial wire was used.[23] We recommend an incision large enough to visualize the humerus and identify with certainty that the ulnar nerve is not at risk. We advocate using a drill guide to pass the wire, reducing the chance of the ulnar nerve or its branches being caught up in the wire.

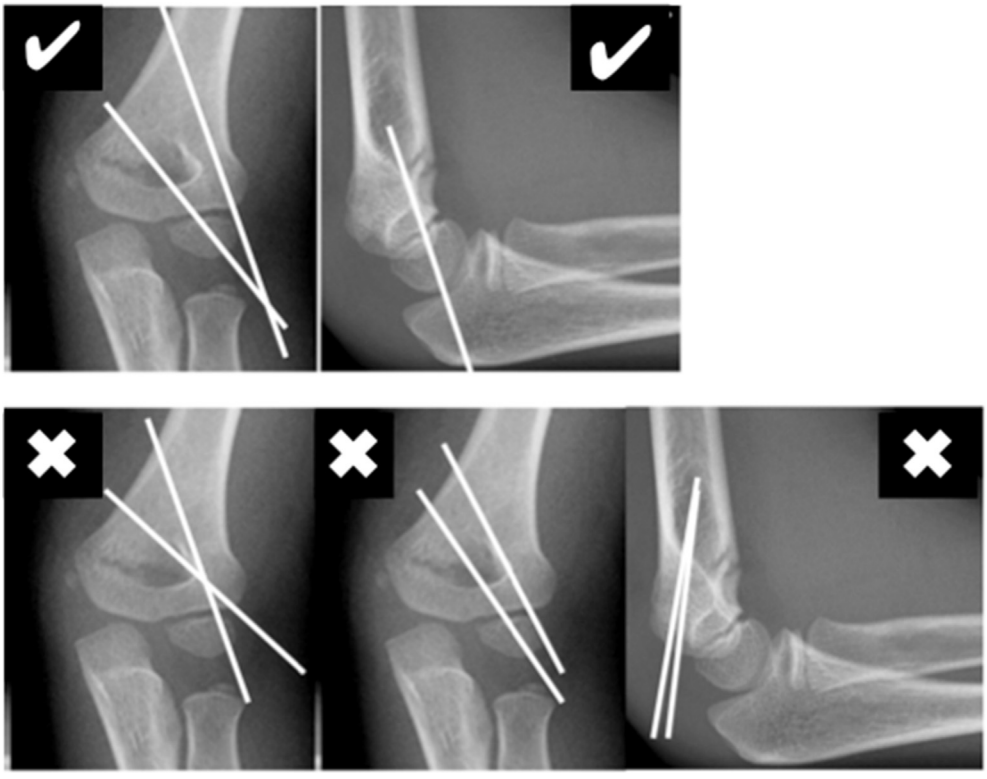

Figure 1 Lateral wiring technique. Increased stability is conferred by ensuring that wires cross outside bone, are divergent with a wide spread at the fracture and engaging both fragments. The lower wire should start medially and traverse the olecranon fossa. The higher wire should start laterally and traverse the lateral column. A posterior entry point should be avoided. The wires should overlie the capitellum on lateral. No gap in the anterior cortex should be seen.

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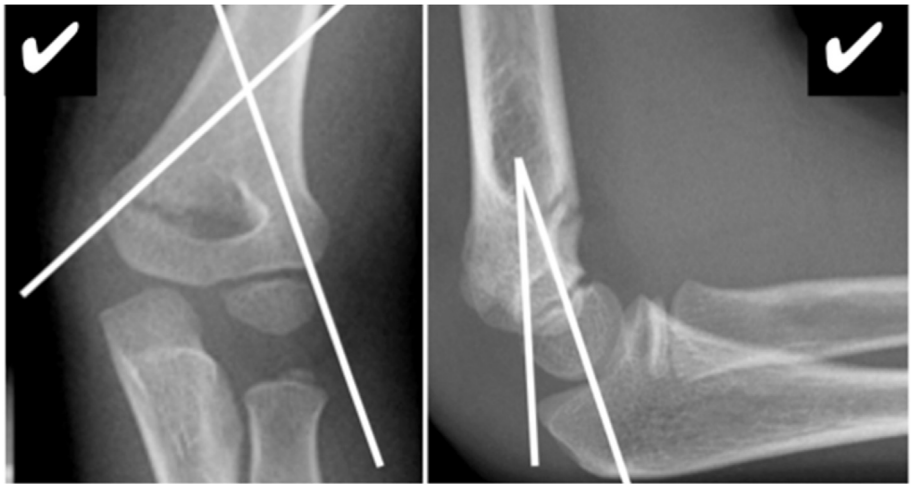

Figure 2 Crossed wiring technique. A wide spread at the fracture site with two wires engaging both fragments and both columns should be achieved. The trajectory of the wires should be steep to avoid crossing at the fracture site. The lateral wire must overlie capitellum on lateral. The medial wire may not, but should be confirmed by direct vision that is secured in the distal fragment.

A number of fracture patterns may not be suitable for lateral wiring techniques. Transverse high supracondylar fracture at the metaphyseal–diaphsyeal junction are often difficult to reduce and percutaneous pinning can be challenging due to the angle of the metaphyseal flare. In high fractures acceptable lateral wiring configuration cannot be achieved and crossed wiring is preferred although can still lead to crossing near the fracture site with reduced stability. Biomechanical studies advocate the use of elastic intramedullary nailing for high metaphyseal–diaphyseal fractures with reported superior stiffness in all directions when compared with standard two-pin crossed wiring.[24]

For mid–low metaphyseal–diaphyseal junction fractures three crossed pin constructs (two lateral and one medial) report better biomechanical stiffness in flexion, extension and valgus but no difference to varus and rotational forces compared with standard two crossed pins. In low fractures no biomechanical difference was demonstrated between two crossed or three lateral wiring techniques.[25]

In fracture patterns amenable to lateral wiring techniques Hamide[25] et al. recommended a starting point in the most distal non articular portion of the capitellum using two divergent wires with one placed parallel to the metaphyseal flare of the lateral humeral cortex and the second crossing the fracture site at the medial edge of the coronoid fossa to provide optimal biomechanical stability and fixation. The authors hypothesized that increased stability is conferred by ensuring pins never cross at the fracture site, utilizing thicker cortices near the olecranon fossa for improved pin purchase and a wide divergent spread at the fracture site conferring maximal rotational control. Lateral pin fixation has been shown to confer adequate stability in the majority of fractures with the exception of medial column comminution and multidirectional instability.

Medial wall comminution is an independent risk factor for loss of reduction.[26] Two lateral pins confer the least biomechanical stability. When an additional third lateral pin is added biochemical studies have demonstrated no significant biomechanical difference compared with standard two crossed pins.[26,27] The stiffest construct remains three crossed wires.[25]

In addition to initial fracture reduction and wire techniques, younger age (majority <8 years) and higher grade of injury have been identified as independent risk factors for redisplacment. Oetgen et al. hypothesized that younger patients with a larger cartilaginous areas is a recipe for reduced surgical fixation.[28] Other authors have reported an independently increased risk of failure to recognize adequate reduction in younger children due to the smaller, non-ossified capitellum, making intraoperative assessment of the anterior humeral line and persistent sagittal plane deformity more difficult. Oetgen[29] retrospectively reviewed 52 patients treated by 11 fellowship trained paediatric orthopaedic surgeons. Gartland 3 fractures had a higher rate of loss of fracture reduction and need to return to theatre in the postoperative period. The authors hypothesized that this represented a more significant soft tissue injury and disruption of the periosteal sleeve leading to inherent instability. Achieving anatomical reduction in cases of multidirectional instability is challenging[15,29,30] and indirect CR techniques may be useful. Leitch[18] et al. reported success with passing two percutaneous lateral K wires into the distal fragment whilst the fracture remains unreduced. The wires were used as joysticks to manipulate the fracture and once satisfactory the two wires were advanced across the fracture site. The reduction and stability are assessed using dynamic fluoroscopic screening. If there was any doubt about stability third lateral wire was added and early follow up recommended.

In our institution it is routine practice to assess the fracture morphology prior to theatre. In fracture patterns amenable to lateral wiring two divergent lateral wires are placed, we strongly advocate moving the image intensifier rather than the arm for the lateral imaging to prevent loss of reduction and iatrogenic instability associated with repeated reduction manoeuvres. Lastly, dynamic fluoroscopic screening of stability undertaken. If necessary a third lateral wire will be placed, if stability is still inadequate a medial wire is placed through an open incision, long enough to adequately protect the ulnar nerve. For high transverse, comminuted or oblique fracture exiting low laterally crossed wire configuration is used. Occasionally a patient will have multidirectional instability, in these patients the position of best reduction is rarely hyper-flexed like an extension type SC fracture but with the forearm at around 90°. A trans-olecranon

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wire has been described to provide temporary stabilization whilst the definitive wires are sited. It can also be useful for the lead surgeon to hold the reduction whilst the assistant passes the wires.

Planning postoperative care

In the UK, early radiographic follow up within 4–10 days is recommended. The argument for early follow-up is based on the early diagnosis of mal-aligned fractures and prevention of late deformity. Loss of reduction may occur in the early postoperative period, typically when adequate stability has not been achieved intraoperatively and reported rates of early displacement are around 14%.[2,31,32] Despite this, other studies report very low rates (1.6%) of displacement actually requiring subsequent intervention such as revision or late mal-union surgery.[33]

As a result some authors advocate against early follow-up with most "fracture displacement" reported as being clinically insignificant. Ponce[2] et al. reported a rate of radiographic displacement of 11% but deemed none of these to be clinically significant and no children had cubitus varus at final follow-up. They also found no statistical difference in the change in reduction whether followed up early or late and no increased risk of complications with late follow-up at the time of pin removal. Authors advocated that assessment of intraoperatively stability is the cornerstone of determining whether early follow-up is required. In cases were the fracture is anatomically (or near anatomically) reduced, is stable on screening and an adequate pinning technique has been used, it may have no benefit to the patient or family at increased cost.[2] However in cases were there is concern regarding fracture stability or wiring technique this should be addressed before leaving the operating theatre and should also be followed up within 5 days, as revision is more difficult beyond 1 week.[2]

Or et al.[7] demonstrated that the average time to loss of fixation is around 7 days and that for the majority of cases the mal-reduction was present on the final intraoperative radiographs.

In our institution all patients are followed up within a week postoperatively as routine practice. It however remains unclear whether early follow-up is beneficial for the vast majority of patients and whether early follow-up has a positive impact on postoperative decision-making when considering early revision and long-term outcomes.[7]

Dealing with early loss of reduction

The treatment of healed, mal-united fractures is well described, though very little is currently reported in the literature about the acceptable limits, diagnosis or management of postoperative mal-alignment prior to union.[7] Comparison of the natural history of 'no intervention', early revision and late intervention is not well described.

Or et al.[7] reported a retrospective review of 396 displaced Gartland 2 or 3 fractures treated operatively. Early revision rate for mal-alignment within 3 weeks was 5%. Mal-alignment was defined as more than 10° displacement in any plane or failure of the anterior humeral line to intersect the capitelleum. The average time lapse between index and revision surgeries was 7.6 days and the vast majority underwent a repeated CR and pinning. At final follow-up all children were pain-free with the majority achieving a full-unrestricted range of movement. Low morbidity was reported with no complications other than mild residual cubitus varus in 10% of children.

Early follow-up is generally recommended to permit the early diagnosis of mal-alignment and to identify children in whom prompt revision surgery would be beneficial. Revision surgery should be considered in children with >10° of coronal or sagittal deformity. Early intervention when the fracture site remains mobile and soft tissues supple potentially reduces the risks associated with late deformity correction.

Dealing with symptomatic late deformity

The gold standard treatment for a symptomatic mal-union of the distal humerus is supracondylar osteotomy. In rare cases of medial growth arrest guided growth with hemi-epiphysiodesis may be useful, but has no role in treatment of a child with a normal physis.

Many different corrective osteotomy techniques have been described; the most commonly used osteotomies are lateral closing wedges or dome osteotomies. The surgical techniques and method of fixation have been modified over time and many variants now exist in current practice.

The French technique, originally described in the 1950s, utilizes a lateral closing wedge through a posterolateral approach. The lateral third of the triceps is detached and reflected proximally with the medial two-thirds elevated sub-periosteally to exposure the distal humerus whilst protecting the ulnar nerve. A laterally based wedge is planned stopping short of the medial cortex. Two screws are passed into the lateral humeral cortex proximal and distal to the planned osteotomy site. The lateral wedge is excised using an oscillating saw and the wedge is manually closed, causing the medial cortex to fracture but leaving the medial periosteal sleeve intact as a hinge. The osteotomy site is well opposed using a tensioned wire loop around the two pre-sited screws. Rotation can be corrected simultaneously with appropriate preoperative planning and rather than using two mid lateral screws, the screws are offset distal anterior and posterior proximal.

Many patients report a prominent lateral condyle postoperatively, which can be both troublesome and unsightly despite good clinical correction of carrying angle and function. This prominence is usually due to a failure to account for the centre of angulation preoperatively. To reduce the prominence the distal fragment can be medialized at the time of surgery. In order to achieve this the medial cortex must also be osteomized with a resultant unstable osteotomy, higher risk of loss of fixation and a more technically challenging surgery.

The dome osteotomy was described and popularized later in the 1970s. A dome osteomy is made in the metaphysis and the distal fragment moved through a lateral arc to correct the carrying angle. Dome osteotomy allows correction closer to the centre of humeral axis of rotation. It therefore provides maximum stability, simultaneous correction of rotational and angular deformities, avoids creating a lateral condyle prominence, causes no lateral translation of the ulnohumeral axis and provides a more cosmetically acceptable scar. Comparative studies have reported better rotational correction using the dome method, but higher rates of complications including inadequate correction, nerve palsy, loss of motion, and circulatory compromise.

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Other osteotomies described include step cuts, interlocking wedges, pentalateral, arch, oblique with de-rotation and medial opening wedge osteotomies.

Common surgical approaches described include the posterior approach, lateral triceps sparing and olecranon osteotomy. Nerve injuries are rarely reported when using a lateral triceps sparing approach compared with rates of up to 14% iatrogenic radial nerve injury using the posterior approach. The radial nerve spirals around the posterior aspect of the humerus lying between the lateral and medial heads of the triceps and is susceptible to injury during proximal muscle splitting. Care should also be taken if utilizing the lateral approach, as proximal extension between brachialis and brachioradialis may expose the radial nerve as it enters the lateral intramuscular septum. Risk of iatrogenic injury to the radial nerve can be minimized by keeping proximal humeral exposure to a minimum and avoiding any unnecessary proximal retraction. Olecranon osteotomy has been reported and gives excellent exposure of the articular surface. It is often unnecessary for this deformity and has significant risks of injury to both the radial and ulnar nerve due to the extensive soft tissue dissection required to perform the osteotomy.

Many techniques for achieving fixation have been described including plate and screws fixation, interfragmentary screws, K wires, staples, tension band wiring or isolated plaster of Paris. Plate and pin fixation are the most commonly used techniques. No difference in rates of overall complications or nerve injury have been demonstrated. Plate fixation is however associated with higher rates of under correction and revision osteotomy. Pin fixation has a higher rate of loss of fixation and return to theatre for revision fixation.

High rates of recurrence are reported in the longer term with rates of up to 84% experiencing an average recurrence of 20° of varus and patient dissatisfaction with the final cosmetic result.[34]

In particular surgical correction for cubitus varus deformity is fraught with difficulties and reported complications range from 7% to 40%.[7,12,35] Frequent complications include iatrogenic nerve dysfunction, residual deformity, growth arrest, non union, osteomyelitis, overcorrection with cubitus valgus, lateral condylar prominence, poor scar cosmesis and restriction of movement. The results are often unpredictable and individuals considering surgery for cosmetic reasons should be counselled appropriately regarding the high rates of complications associated with corrective surgery.[36]

Key points

- Surgeons inexperienced in treating supracondylar fracture are more likely to have inadequate reduction and early loss of fixation
- Initial reduction is key — do not rely on remodelling potential even in young children
- Proficient selection of wiring configuration and good technical execution will minimize late displacement
- Final dynamic assessment of intraoperative stability is essential, with steps taken to address instability
- If there are concerns about stability early follow-up is recommended to identify cases that would benefit from early revision surgery

Slipped capital femoral epiphysis

Slipped capital femoral epiphysis (SCFE) is a common injury during peri-adolescent childhood, with an incidence of 1 per 1000 children.[39–41] A working knowledge of initial management, surgical strategies, common complications and late treatment options are imperative to all units receiving paediatric trauma.

The epiphysis is not actually the structure which 'slips'; instead, it remains within the acetabulum in its anatomic location and the metaphysis translates anteriorly and externally rotates. The classical age group is 10–16, during the adolescent 'growth spurt', due to a number of morphological changes occurring within the physeal region. During this time of growth the perichondral ring thins and the undulating mammillary processes unlock causing inherent instability. These changes, coupled with the relatively vertical orientation of the physis at this age (165° comparative to 125° at the end of growth), creates a perfect storm of a physiologically weakened growth plate subject to vastly increased shear forces.

Risk factors most closely correlated with SCFE are male gender, obesity and certain ethnicities (African, Polynesian and Hispanic). Associated conditions have been described including hypothyroidism, renal osteodystrophy, growth hormone deficiency, panhypopituitrism and Down's syndrome.[39]

SCFE can be classified by stability or by radiographic appearance using the Southwick angle. Loder described the inability to weight bear with crutches as the defining risk factor for subsequent development of avascular necrosis (AVN) of the femoral epiphysis. Stable SCFE has a reported risk of less than 10% compared with 24–47% in unstable SCFE.[42] This provides important early prognostic information to adequately counsel patients and their families on the risk profile of the affected hip. The Southwick angle allows guidance on the operative management of the slip. The degree of slip is classified into mild (<30°) moderate (30–50°) and severe (>50°). The classical treatment for SCFE is in situ pinning. In cases of severe slips however it may be highly challenging or technically impossible to pass a screw and other options may need to be explored. In our practice, we often use cross-sectional imaging to decide whether in situ pinning is advisable in severe stable SCFE.

Finally SCFE can be classified by chronology, acute (<3 weeks), chronic (>3 weeks) and acute on chronic (sudden exacerbation on background of pre-existing symptoms). This can have implications on both the prognosis and surgical management due to the morphology of the proximal femur. In chronic SCFE progressive remodelling may mean a significant shepherd's crook deformity may already be present.[43]

There is no role for non-operative management of SCFE in a developed healthcare system. The traditional gold standard treatment for SCFE is in-situ pinning. Other options include open reduction with decompression and osteotomies to shorten the femoral neck and reduce the epiphysis with less tension (this can be carried out via an anterior approach or surgical dislocation).

Two major complications causing late deformity in SCFE are AVN of the femoral epiphysis and residual cam deformity leading to subsequent femoro-acetabular impingement. Long-term consequences include degeneration, which can be particularly rapid following AVN, and the need for further reconstruction surgery or arthroplasty.

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Avascular necrosis of the femoral head

AVN is one of the most described complications of SCFE and much of the published literature has focused on strategies to reduce the risk of AVN and lifetime risk of further hip surgery. Collapse of the femoral head is due to death of the organic elements of bone, absence of biologically active cells and thus absence of normal bone turnover and healing of micro-fractures. In mild cases salvage procedures can be attempted but in severe cases arthroplasty may be the only option.[44] A large degree of the risk of AVN is non-modifiable and directly relatable to the initial presentation.

Surgical strategies to reduce risk: there are a number of strategies that orthopaedic surgeons can utilize to minimize the risk of developing AVN in SCFE. It is recommended that children are admitted and remain strictly non-weight-bearing as soon as a SCFE is suspected or diagnosed. This reduces the risk of converting a potentially stable SCFE to an unstable or displaced SCFE with a higher inherent risk of AVN and poor prognosis. Stable SCFE is treated by pinning in situ whenever technically possible and the timing of intervention is not linked to risk.

In UK practice acute fixation is generally recommended for unstable slips within 24 hours or, if this time window is missed, strict bed rest for 2 weeks prior to fixation.[45] This is in an effort to minimize the second hit of surgery through already inflamed tissue. The increased inflammatory response coupled with raised intracapsular pressure from the fracture haematoma may prevent adequate vascularization of the epiphyseal fragment and hence increase the risk of AVN.[46]

In situ pinning remains the gold standard treatment for SCFE that does not require a reduction manoeuvre. This can be undertaken freehand or using a fracture table, although no overt traction or reduction manoeuvres should be performed. Standard CR techniques have been shown to increase the incidence of AVN of the epiphyseal segment and are not recommended.

In cases suitable for in situ pinning image intensifier control is used to pass a guidewire into a centre—centre position in the epiphysis. It is expected that the pin should cross the femoral neck from an anterior starting point in the metaphysis. It is important that the entry point is not too proximal on the femoral neck however, as we have seen this lead to a 'windscreen-wiper' effect and failure with a requirement for revision surgery.

In unstable SCFE, a 'serendipitous reduction' may occur spontaneously on positioning. Studies have demonstrated an increased risk of AVN in this cohort following a complete reduction. It is hypothesized that this reflects a raised intracapsular pressure of up to threefold. If a serendipitous reduction has occurred on table, progression to an open decompression should be considered.[47]

In cases of acute, severe SCFE in situ pinning may be technically impossible, may result in an unacceptable deformity or a high risk of intraoperative uncontrolled serendipitous reduction. Alternative open surgical reduction techniques should be considered. The Parsch technique utilizes an anterior approach to the hip and the surgeon uses a finger to perform a gentle controlled reduction of the metaphysis onto the epiphysis after opening the capsule followed by fixation with smooth K wires (we use this technique but with screw fixation). The authors have demonstrated an exceptionally low AVN rate of 4.7% and believe that by decompressing the intra-capsular haematoma the 'second hit' of surgical trauma is negated and the femoral head remains viable.[48]

A modified Dunn technique has also had good success in realignment without interruption of the epiphyseal blood supply. This involves performing a trochanteric osteotomy and raising a subperiosteal flap anteriorly which excludes the short external rotators and hence the retinacula vessels along with it. This allows surgical dislocation of the hip, realignment and fixation without interrupting the blood supply. The rates of AVN reported with this technique are under 5%.[49,50] There have been reports of hip instability, presumably due to femoral neck shortening and loss of offset.

Other options include a cuneiform shortening osteotomy. This is performed through an anterior approach without dislocation of the hip. A trapezoidal wedge is excised from the femoral neck, causing shortening of the femoral neck and allowing tension free realignment of the metaphysis on the epiphysis.[51] Multiple studies have been published reporting AVN rates varying between 3% and 30%. In a recent comparative study the cuniform osteotomy was found to have a lower incidence of AVN than closed in situ pinning for severe slips.[47]

In cases of chronic SCFE with remodelling there is no opportunity to reduce the SCFE without osteotomy. In mild or moderate cases pinning in situ is used, minimizing the risk of AVN and accepting that symptomatic late deformity such as femoro-acetabular impingement (FAI) may need to be addressed once the patient is skeletally mature. However in severe cases the deformity may need to be addressed at the time of diagnosis and the risk of AVN is higher. This can be undertaken with a cuneiform osteotomy via an anterior approach or a surgical hip dislocation.

There is also controversy regarding the optimum surgical fixation for SCFE and there is further debate around the type of pins to use.[52] Classically, fully or partially threaded cannulated screws have been used either as subchondral positional screws or to compress the physis preventing further growth. This prevents recurrence of SCFE, as the epiphysis is unable to grow off the top of the screw. In recent years there has been a vogue towards smooth tipped growing screws, although this is not routine practice in the UK. These devices allow ongoing growth of the femoral neck and have the perceived advantage of reducing leg length discrepancy by allowing further growth, restoration of offset and thus prevention of abductor fatigue. As the child grows it also permits the area of deformity to move further away from the acetabulum and potentially prevent impingement.[45] These children may need revision surgery and must be closely monitored due to the potential for recurrence of SCFE when the epiphysis outgrows the screw length. In our unit, we currently reserve this technique for the uncommon situation of a SCFE in a child of 10 years of age or younger.

Managing established avascular necrosis

Established AVN can be a life-changing complication of SCFE; it results in femoral head collapse and an ovoid, incongruent joint often associated with a metaphyseal cam lesion which can hinge on the superior—lateral acetabular wall. Diligence must be taken to ensure the exact extent of AVN is known when planning

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surgery. Cross-sectional imaging and an examination under anaesthetic arthrogram is also imperative to gain better understanding of the morphology of the femoral head, to identify an impingement lesion and whether pain is limiting the range of movement.[44]

Joint preservation surgery is used in an attempt to slow progression of the degenerative changes in established AVN. With rapid advances and increasing longevity and promising outcomes in modern arthroplasty consideration should be given to the long term implications of altering the bony anatomy and subsequent impact on later surgery. Joint preservation options include containment with a lateral shelf osteotomy in order to improve uniform loading of the femoral head. This may be combined with proximal femoral osteotomies depending on the location of the AVN. The aim of proximal femoral osteotomy is to rotate the avascular segment away from the weight-bearing zone. This usually involves valgus and extension re-orientation of the femoral head comparative to the shaft.

Joint fusion is still occasionally recommended in highly symptomatic cases with severe deformity and who have a pre-existing severe restriction in range of movement. In a cohort of all-cause paediatric hip arthrodesis from Stanmore[44] the authors reported no conversions to total hip arthroplasties at 10 years follow up. It is well recognized however that hip fusion leads to high rates of back and contralateral limb problems. The risk of revision surgery during the child's remaining lifespan is high and conversion to total hip arthroplasty in the context of a hip fusion with defunctioned abductors is a complex undertaking, with higher associated morbidity.

The gold standard late treatment of a skeletally mature individual with debilitating degenerative changes is a total hip arthroplasty. Stanmore report good results with low revision rates in these patients. However patients and their families need to be counselled appropriately regarding lifestyle and career choices, likelihood of multiple revisions and functional impact over the projected lifespan of the child.

Residual deformity and femoro-acetabular impingement

As the metaphysis translates anteriorly off the epiphysis the femoral morphology is significantly altered. The head–neck junction becomes retroverted in the axial plane and the hip has a varus attitude in the coronal plane. This results in the metaphysis abutting the antero-superior acetabulum which unless there is significant remodelling can create labral tears and subsequent degeneration of the hip. This is now recognized as an intermediate stage between SCFE and an arthritic hip.[53–55]

As described above pinning in situ is traditionally accepted as the 'safest' surgical management in terms of AVN risk however due to the absence of anatomical reduction is more likely to result in FAI at skeletal maturity. There is increasing interest in surgical strategies to treat post SCFE FAI before it causes labral tears and subsequent arthritis. These techniques can be broadly divided into two categories – realignment osteotomies and osteoplasty. On occasion both techniques are required for management of the impingement lesion.

Chondrolysis

Chondrolysis or acute cartilage necrosis has been reported in up to 20% of patients post-SCFE with a severe slip increasing the chance of chondrolysis to 28%.[56] This is unfortunately an irreversible complication of SCFE and after delamination of the cartilage from the femoral head of the acetabulum patient who are highly symptomatic may undergo arthrodesis or arthroplasty.

Joint-preserving surgery

Numerous reorientation osteotomies for SCFE have been described. The closer the osteotomy is to the deformity the more powerful the correction but the higher the risk of inducing AVN.

In addition to the osteotomies described for AVN, Barmada and Kramer described a base of femoral neck osteotomy, which corrects the femoral retroversion allowing improved external rotation of the leg. It has a low reported rate of AVN at 3.6% however only moderate correction can be gained with this osteotomy. It can be combined with osteoplasty for improved clearance.

Southwick and Imhauser popularized the intertrochanteric osteotomy post-SCFE. The osteotomy site is extra-capsular and is therefore hypothesized to be protective against AVN. The authors reported good results with 83% rate of satisfactory outcome at 24 years. Unfortunately the Imhauser osteotomy increases the relative retroversion of the femoral head. Due to the deformity created by the osteotomy, femoral component insertion in total hip arthroplasty can be more difficult.[57,58]

Osteoplasty is another option first described by Heyman who excised the 'bump' at the same time as pinning SCFE. This was abandoned after comparable results were published without osteoplasty. Osteoplasty does not realign the proximal femur simply removes the impingement lesion to improve range of motion and reduce pain. Osteoplasty can be performed open during surgical hip dislocations as part of a combined procedure or arthroscopically in isolation.[59]

A combination of an Imhauser osteotomy combined with osteoplasty has had some success with an improvement in the non-arthritic hip score however it failed to reach significance ($P = 0.056$).[60]

Total hip arthroplasty

The final option for many symptomatic patients with significant AVN, FAI or chondrolysis consequent upon SCFE is a total hip replacement. Halvorsen[61] has recently published data on the outcomes of total hip arthroplasty in patients under 21years according to the Nordic Arthroplasty Register. All-cause survival was 86% at 10 years and 73% at 15 years with no predisposition for revision between uncemented and cemented implants. Clinical outcomes from the same group found a mean Harris Hip Score of 83/100 indicating good functional outcomes as well as longevity of implants.[62] With advancing materials available implant survival may be increasing in this age group with a recent British study having survivorship of 96% at 5 years[63] and similar results at 3.8 years in Australia[64] although it is unclear if this will continue and surpass the data from Scandinavia. Despite this it is important to recognize that the survivorship data is worse than in the general population with comparable implants demonstrating 93.78% (uncemented ceramic on ceramic) and 96.23% (cemented ceramic on polyethylene) survival at 14 years respectively in the 2018 National Joint Registry report.[65]

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It is also unclear how a hip replacement in young adult life affects the emotional and psychological development of these patients. An example from a recent study from Finland demonstrated up to a 60% reduction in birth rates and probability of having a child for both male and females who underwent a total hip replacement between the ages of 15–45.[66]

Despite good functional results it is not a management decision to be taken lightly and can make a remarkable impact the course and quality of a young patient's life. ◆

Key points

- Strategies to reduce modifiable risk factors for avascular necrosis (AVN) and femoro-acetabular impingement (FAI) in slipped capital femoral epiphysis (SCFE) are essential in reducing long-term morbidity and degenerative disease
- Treatment of unstable severe SCFE remains controversial. Consideration should be given to the timing of surgery, open decompression and reduction
- Early referral of children and young adults with AVN, FAI or chondrolysis to tertiary paediatric centres and transitional services is recommended
- Patients and families should be counselled early regarding the long-term prognosis, lifestyle impact and likelihood of further surgery

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