GETTING IT RIGHT THE FIRST TIME

Optimizing surgical treatment for unforgiving pediatric elbow injuries

Lisette C. Langenberg

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ISBN: 978-94-6537-213-6
Cover design: Yske Elsenga and Fedde Elsenga
Lay-out & Print: Ridderprint | www.ridderprint.nl

Getting it Right the First Time:

Optimizing surgical treatment for unforgiving injuries in pediatric elbows

In één keer goed:
Optimalisatie van chirurgische behandeling
voor genadeloze letsels van de elleboog bij kinderen

Proefschrift ter verkrijging van de graad van doctor
aan de Erasmus Universiteit Rotterdam
op gezag van de rector magnificus

en volgens besluit van het College voor Promoties.

De openbare verdediging zal plaatsvinden op woensdag 25 maart 2026
om 15:30 uur

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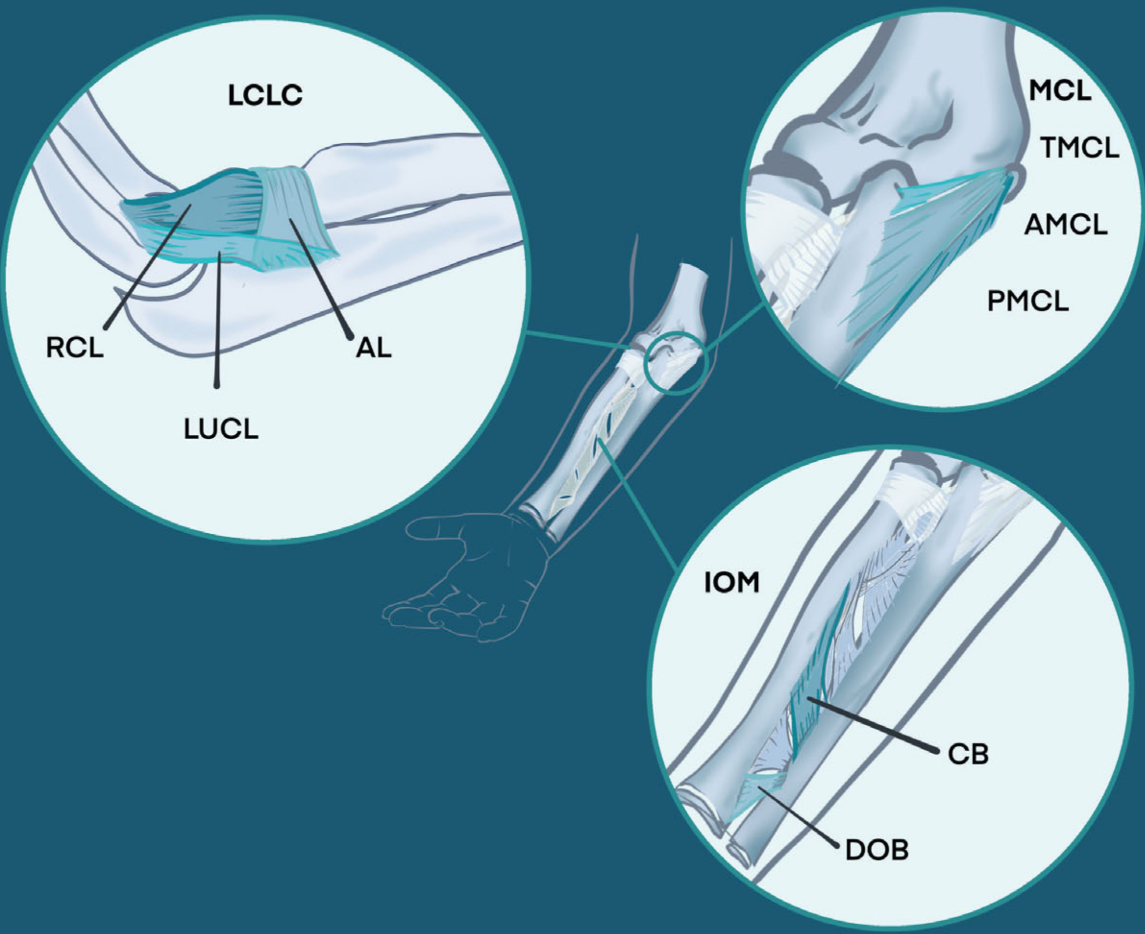

CHAPTER 01

Introduction

Introduction

Anatomical background and biomechanics

The elbow includes multiple joints in one joint space. The ulnohumeral hinge on the medial side is involved in flexion and extension of the elbow. The radiocapitellar joint laterally, and the proximal radioulnar joint (PRUJ), are both involved in rotation. Incongruency of these joints may therefore influence the range of motion of both the elbow and the forearm.

Strong ligaments keep the radial head and ulna aligned with the distal humerus (Figure 1A and 1B). Laterally, the lateral collateral ligament complex (LCLC) ascertains radiocapitellar alignment in varus and posterior rotatory movements. The LCLC comprises of an oblique posterolateral band that runs from the lateral epicondyle to the ulna, where it inserts on the supinator crest (lateral ulnar collateral ligament, or LUCL), and the isometric radiocapitellar band (radial collateral ligament, or RCL[1]), that blends with the annular ligament[2]. The annular ligament lies as a tight band around the radial neck and attaches to the ulna on the volar and dorsal side. It ensures congruency of the proximal radioulnar joint and stabilizes radiocapitellar rotation. The RCL functions mainly as a stabilizer in extension and the LUCL prevents radial head dislocation in flexion.

The medial collateral ligament also contains three distinct ligamentous structures, of which the anterior medial collateral ligament (AMCL) is the most important. It runs from the medial epicondyle to the sublime tubercle of the ulna. The transverse ligament has no evident action in stabilizing the elbow joint, and the posterior, fan-like bundles are a thickening of the posterior capsule, which are optimally tensioned in 90 degrees flexion[2].

In pronation and supination of the wrist, the radial bone rotates around an axis which runs from the radial head proximally to the ulnar head distally. The forearm may therefore be seen as one long joint consisting of both the proximal and distal radioulnar joint (PRUJ/DRUJ), interconnected by both bones of the forearm. This forearm joint is stabilized by the interosseous membrane (Figure 1A and 1B), the annular ligament and the proximal and distal radioulnar capsule and ligaments. To obtain adequate forearm rotation, the complex ‘forearm joint’ therefore requires an optimal balance between mobility and stability.

On the volar side, the anatomy of the elbow comprises of a crisscross of muscle attachments, several nerves that have varying bifurcations, a network of veins, and the brachial artery that divides into the ulnar and radial artery. All these structures have to enable movement. Flexion and extension of the elbow are the most comprehensible movements, which are mainly effectuated by the brachialis, biceps and brachioradialis muscle (flexion), and the triceps muscle (extension). Several muscle groups are involved in rotating the forearm: supination is mainly obtained by action of the biceps muscle and supinator muscle (Figure 2), pronation is mainly obtained by action of the pronator teres and pronator quadratus muscles (Figure 2). This delicate anatomy may be hindered in function in case of a fracture, rupture or a dislocation of one of the joints of the forearm or elbow .

Several important nerves run near the elbow, down to the hand and wrist. Medially, the ulnar nerve emerges from the intermuscular septum and the medial triceps, and courses via the ulnar sulcus and through the fascia of the flexor carpi ulnaris muscle[3]. On the radial side, the radial nerve runs anterior to the elbow capsule, where it bifurcates in the superficial radial nerve (RSN) and the posterior interosseous nerve (PIN). The RSN has a purely sensory function: it provides sensitization to the skin of the thumb and dorsal side of the index finger. The PIN runs through the supinator muscle, to innervate all the extensor muscles distal to that point[4]. Both nerves may be encountered in surgical approaches to the elbow joint or proximal radius.

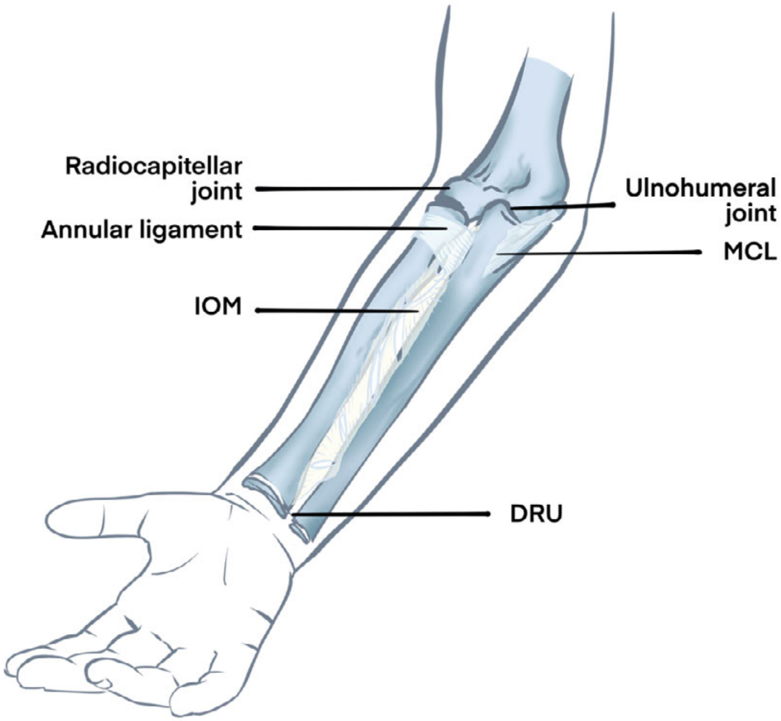

Figure 1A. Medial / anteroposterior view of the elbow and forearm which shows the humeral, ulnar and radial bones. The elbow hinge is formed by the ulnohumeral joint. Forearm rotation requires a delicate balance between radiocapitellar joint and the radioulnar joints. The interosseous membrane (IOM) stabilizes the forearm when the radius rotates around the ulna. DRU: distal radio-ulnar joint; MCL: medial collateral ligament.

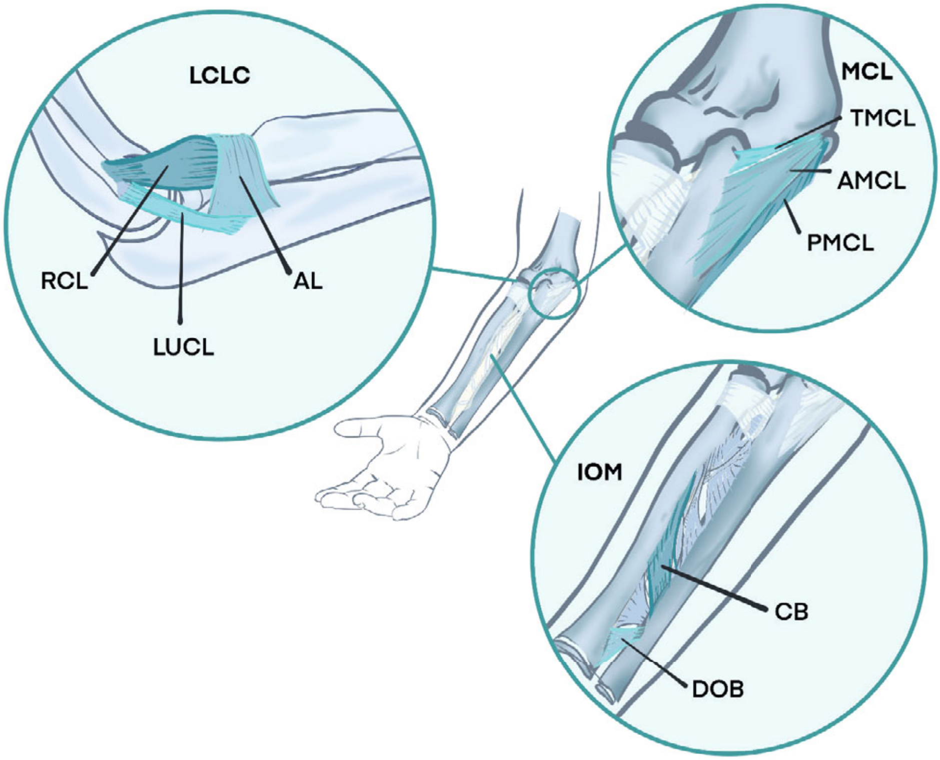

Figure 1B. Zoomed in detailed areas of figure 1A depicting important ligaments. Upper left corner: LCLC (Lateral collateral ligament complex); LUCL (Lateral ulnar collateral ligament) is important in flexion and stabilization of posterolateral rotation; AL (Annular ligament) stabilizes the radial head, and RCL (radial collateral ligament) is mainly important in varus stress. Right top corner: MCL (Medial collateral ligament): The most important ligament is the AMCL (anterior Medial Collateral ligament), which resists valgus stress. The PMCL (posteromedial collateral ligament) is taut in flexion but is not an important stabilizer. The TMCL (Transverse medial ligament) runs from tip olecranon to coronoid ridge and is the least important medial ligament. The IOM (interosseous membrane) is highlighted in the right lower corner. The most important distal structures are the DOB (distal oblique band) and the CB (central band).

Other important structures are the branches of the small cutaneous nerves around the elbow, which are situated in the subcutaneous tissue. The lateral antebrachial cutaneous nerve (LABCN) originates from the musculocutaneous nerve and emerges from underneath the biceps muscle and runs down the lateral 3/4 of the lower arm. It provides sensation to the lateral forearm. The medial antebrachial cutaneous nerve (MABCN), gives sensation to the medial skin of the forearm. It originates from the brachial plexus at shoulder level and courses down from underneath the fascia of the brachialis muscle to the elbow, alongside the short head of the biceps muscle. It crosses the Basilic vein in the lower arm. The Ulnar nerve runs behind the intermuscular septum, through the sulcus behind the medial epicondyle, into the flexor carpi ulnaris muscle (Figure 3).

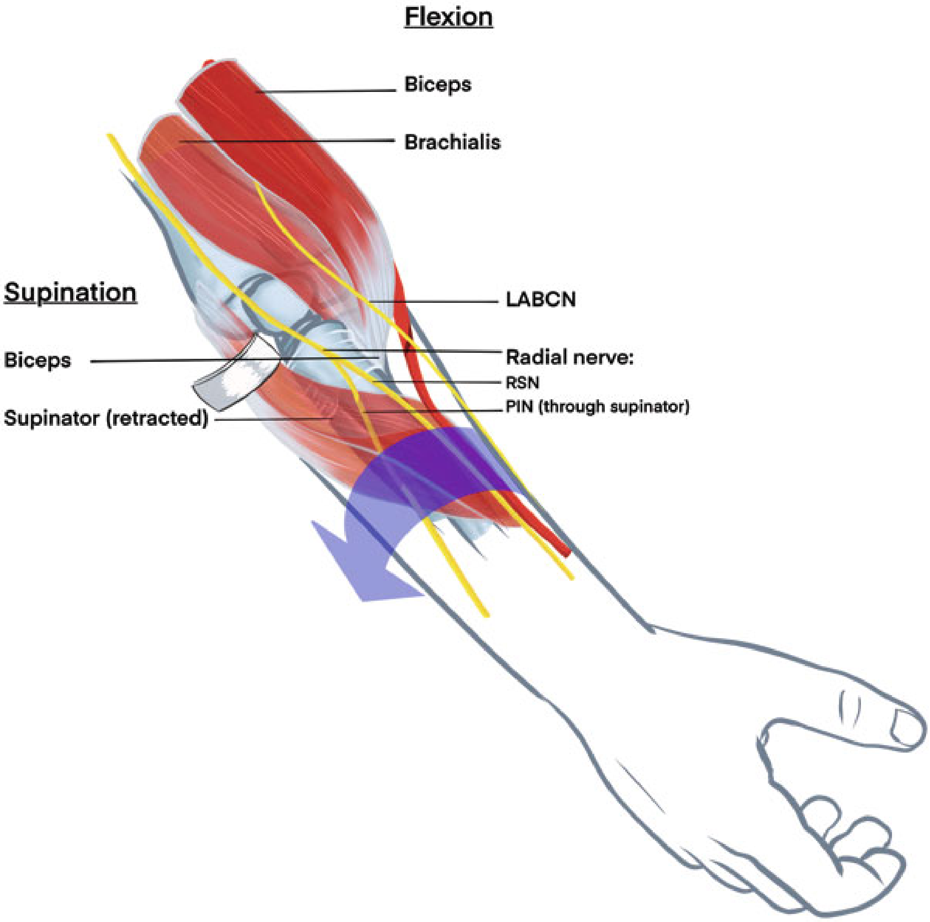

Figure 2. Lateral view of the elbow and forearm with structures involved in flexion and / or supination. The radial head is seen behind the retracted supinator muscle, with the annular ligament surrounding the radial neck. The biceps attaches to the bicipital notch on the radius, and causes both elbow flexion and a supinating motion of the forearm on contraction. The radial superficial nerve (RSN) runs distally alongside the radial artery. The posterior interosseous nerve (PIN) runs through the supinator muscle to the posterior side of the radius. The lateral antebrachial cutaneous nerve (LABCN) emerges from underneath the biceps muscle. The underlying brachial muscle attaches to the ulna and is the most powerful elbow flexion muscle.

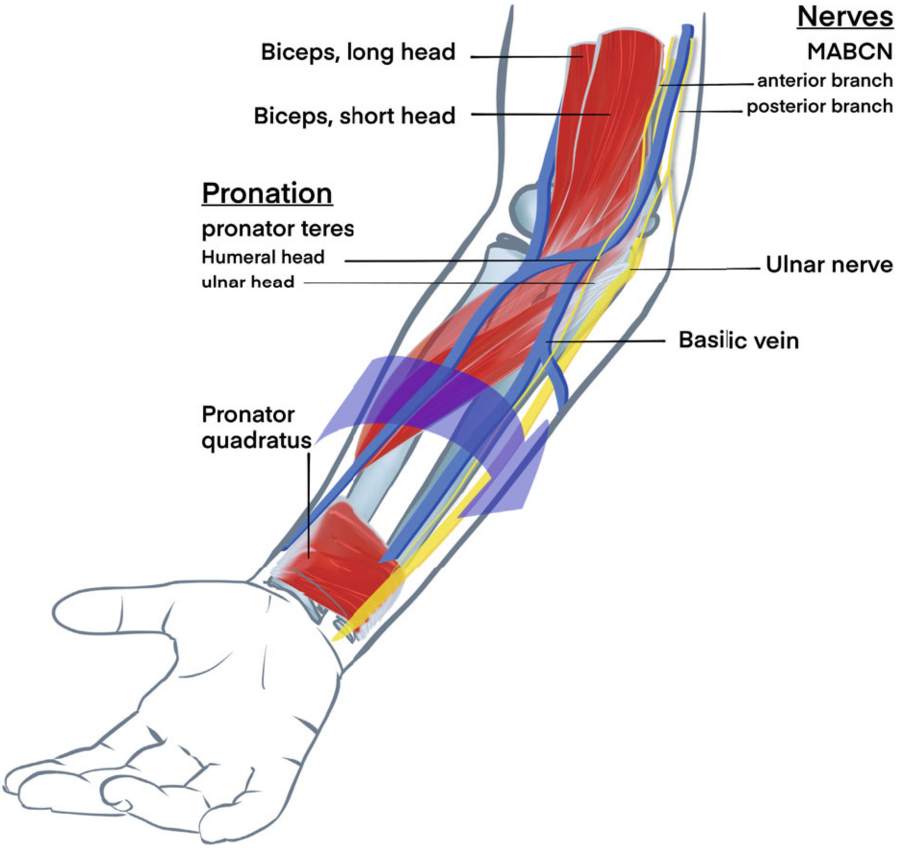

Figure 3. Medial view of a pediatric elbow and forearm. Pronation is mainly effectuated by the two heads of pronator teres, which run from the medial side of the humerus and ulna to the shaft of the radius, and the pronator quadratus, which is situated on the volar side of the wrist. MABCN: medial antebrachial cutaneous nerve.

Trauma classifications and mechanisms

Over the past decades, several specific trauma mechanisms have been identified and named after the surgeon that recognized them first. The Monteggia injury (figure 4a) includes a fracture or a bowing of the ulna combined with a radial head dislocation[5]. The Galeazzi fracture comprises of a distal ulna dislocation and a radial shaft fracture (Figure 4b[6, 7]). In an Essex-Lopresti injury, the forearm becomes unstable in an axial direction ([8, 9]Figure 4c). The Essex-Lopresti injury pattern is characterized by a fracture of the radial head, a disruption of the interosseous membrane and a dislocation of the distal radioulnar joint[10]. Essex-Lopresti injuries are also referred to as longitudinal radio-ulnar dissociations (LRUD), because the IOM ruptures over the entire length of the forearm which may cause a shift (dissociation) in the PRUJ or DRUJ[11].

Figure 4a. Monteggia injury: a proximal ulna fracture is present, in combination with a radial head dislocation. The annular ligament may rupture or become entrapped in the radiocapitellar joint or in the PRUJ. Figure 4b. Galleazzi injury: radius shaft fracture, distal ulna dislocation. Figure 4c. Essex-Lopresti injury: a proximal radius fracture is present (in this figure: radial neck fracture) in combination with a disruption of the IOM distal to the fracture.

Elbow and forearm injuries in children

In children, 80% of fractures is found in the upper extremity, which may be explained by a trauma mechanism that often includes a fall on the outstretched hand[12]. Pediatric bone is more cartilaginous than in adults, and growth plates form weak spots which may become part of avulsion fractures[13]. Pathophysiologic pathways of elbow injury in children may therefore differ from what is known in adults[14, 15]. Thereby, historical concepts regarding fracture incidence are changing due to the involvement of young children in organized sports[16]. Specific fractures around the elbow, like proximal radial fractures, are therefore now seen more frequently.

Fractures around the elbow are mainly classified by radiologic criteria (fracture characteristics on plain X-rays). Simple, or isolated fractures, may however be part of larger, more complex injury, which includes ligament injuries or reduced dislocations[17]. Occult fractures are also quite common[16].

Adequate diagnosis of elbow injury in children may be challenging. Clinical examination is difficult in the painful or stressed child, and physical examination of instability is unreliable because of physiological laxity of the joints in young children. The appearance of ossification centers at varying ages complicates the radiologic recognition of fractures or avulsions[18, 19].

Late sequelae: unforgiving injuries

In children there is another factor that comes into play: growth. Growth may be “your friend”, as grossly angulated fractures may remodel to acceptable positions if the child ages. Unfortunately the proximal radial physis only contributes for about 25 percent of the total length growth of the radial bone[20], which results in less remodeling by growth than distal radius fractures.

There are cases in which growth is not your friend[21]. If a radial head becomes dislocated chronically, the lack of pressure on the radial head causes the articular surface to bulge and become 'dome-shaped'. The radial head circumference enlarges and a relative ulna shortening occurs[22]. Clinical symptoms of such a missed radial head dislocation are mild at first, because the radial head rotates freely in its dislocated position. However, if effects of growth lead to deformation, the aforementioned effects become irreversible and corrective surgery becomes more complex and less successful.

Apparently "simple" fractures, such as an ulna fracture or a radial neck fracture, may be part of a more complex injury, like a Monteggia fracture-dislocation or a dislocation of the elbow joint[18, 19]. Many late sequelae have been described following such injuries, such as ossifications of missed avulsion fractures or irreducible chronic radial head dislocations due to deformations caused by the effect of growth. A range of clinical symptoms may be seen, which often have long-standing effects. It is of utmost importance that awareness of these unforgiving injuries rises among medical professionals, so timely intervention is possible.

Aims of this thesis

This thesis aimed to gain more insight in recognizing unforgiving injuries in pediatric elbows and improvement of surgical corrective procedures.

Especially in children, all efforts should be taken to optimize outcome, to minimize surgical complications and to decrease the risk of late sequelae. This includes attention for small details, like the prevention of injury to the small nerves surrounding the elbow. In current research on the cutaneous nerves around the elbow, the position of cutaneous nerves is indicated in centimeters to anatomical landmarks, based on anatomical studies in adult human specimens. In children, these set distances are not useful due to their shorter stature.

Part one of this thesis therefore focuses on adequate depiction of the cutaneous nerves around the elbow using Computer Assisted Surgical Anatomical Mapping (CASAM). This technique proved to be useful in determining the course of small nerves and enabled the evaluation of safe zones for surgery around the knee and the wrist [23]. Currently, the estimated course of the delicate cutaneous nerve branches around the elbow is based on anatomical studies in adults. Distances to anatomical landmarks are set in centimetres, which makes estimation of the proximity of nerve branches to surgical fields difficult in children and patients with varying body compositions. In

CASAM, the relative distance to anatomical landmarks is used, depicting the course of several anatomical specimen in one summarizing overview image. The goal was to identify potential safe zones for surgical procedures around the elbow. Hypothetically, defining safe zones would decrease postoperative neurologic complications like changed sensation of the skin and painful neurinomas.

Part two is dedicated to increasing knowledge regarding pediatric trauma mechanisms and predicting the presence of an unforgiving injury. It includes two reviews on pediatric radial neck fractures. The first paper includes a large meta-analysis of individual patient data evaluating associated injuries in pediatric radial neck fractures. The trauma mechanism is evaluated by deducing the biomechanic pathway. In the second review on radial neck fractures, outcomes for specific fracture- and treatment groups are compared to identify the best treatment for these types of fractures.

Part three aims to determine the best surgical treatment for missed Monteggia lesions (MM) in children. The negative, deforming effect of growth on the radial head may be seen as soon as four weeks following MM[24]. Current literature on this subject acknowledges a worse outcome if there is a dome-shaped radial head or enlarged radial head circumference, but clear cut-off values which contraindicate surgery have not yet been set[25]. In part three, quantitative three-dimensional CT-scanning is used to measure radial head concavity and the radial head articular surface, aiming to find a tool that may be used to assess radial head deformation in missed Monteggia lesions.

Ideally, surgical correction should include restoration of elbow and forearm biomechanics by correcting the alignment of the ulna and reducing the radial head[26]. Corrective surgery may include an open debridement of the radiocapitellar joint, an ulna osteotomy, and/or an annular ligament reconstruction. It is not yet known which steps in these surgical procedures are essential. Therefore a systematic review of the available literature was done to provide an overview of pearls and pitfalls of corrective surgery for missed Monteggia lesions in children. The results are presented in chapter seven.

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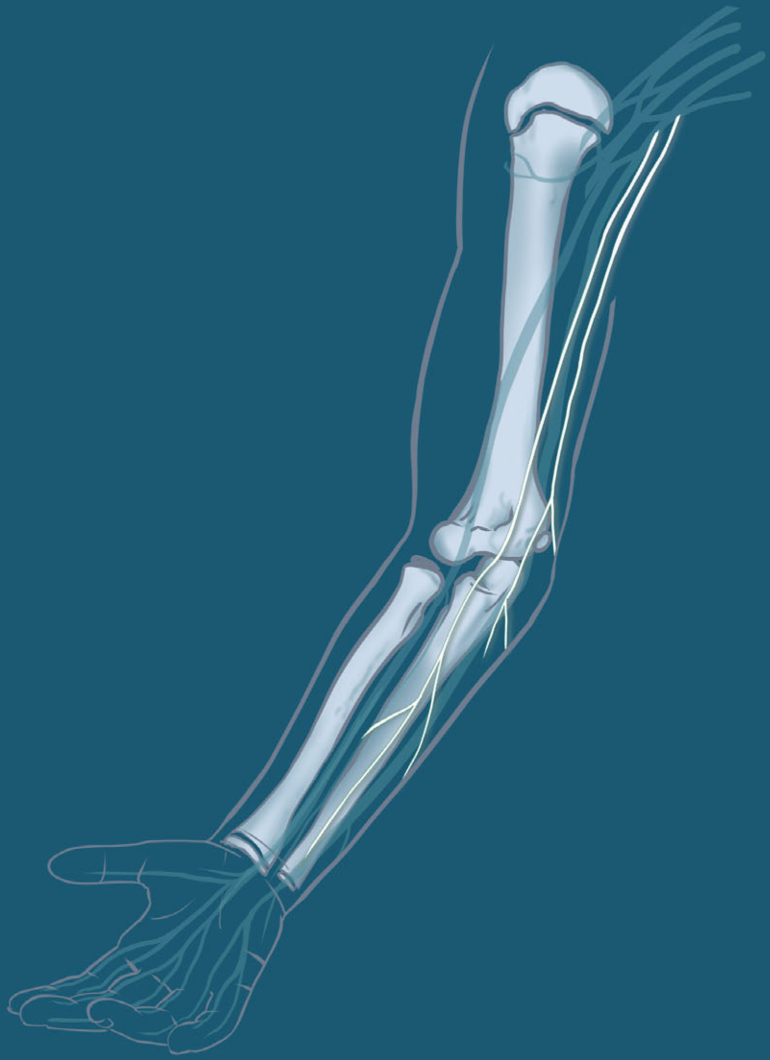
PART ONE

1

Computer-assisted surgical mapping (CASAM) of cutaneous nerves around the elbow



CHAPTER 02

Computer-assisted surgical anatomical mapping (CASAM) of the medial antebrachial cutaneous nerves:
is there a safe zone for surgery?

Langenberg LC, Poublon A Hofman L, Kleinrensink G.J, Zuidam JM, Eygendaal D

Under revision, Journal of Hand Surgery (European Volume)

Abstract

Despite varying body composition in patients, the position of cutaneous nerve branches is registered at a set distance to anatomical landmarks. In this study, the exact course of the medial antebrachial cutaneous nerve (MABCN) was assessed with computer assisted surgical anatomical mapping (CASAM), describing their location at a relative distance to anatomical landmarks in ten human specimen of the arm. The aim was to identify a safe zone free of cutaneous nerve branches, relative to anatomical landmarks. Following CASAM, a large zone potentially containing cutaneous nerves remained. There was a high variability in the number of branches and nerve positions around the medial epicondyle, without a clear safe zone near the medial epicondyle. Surgeons should be aware that the course of MABCN branches shows a wide variety which necessitates a careful dissection to identify this nerve to avoid damage by traction or transsection in any invasive procedure around the medial side of the elbow

Level of evidence: III

Introduction

The cutaneous nerves around the elbow are known to have variable courses among individuals[1-3]. Several studies on the medial antebrachial cutaneous nerves (MABCN) distinguish between an anterior branch and a posterior branch[3, 4]. Both emerge directly from the medial cord of the brachial plexus. In the upper arm, the MABCN branches course down near the medial border of the biceps brevis muscle, near the basilic vein (Figure 1[5, 6]). The position of the MABCN about the medial epicondyle varies, and multiple branches may be present anterior and posterior to the epicondyle. A large variability has been demonstrated in the course and number of branches, as many as 3-8 bifurcations may be present [7, 8].

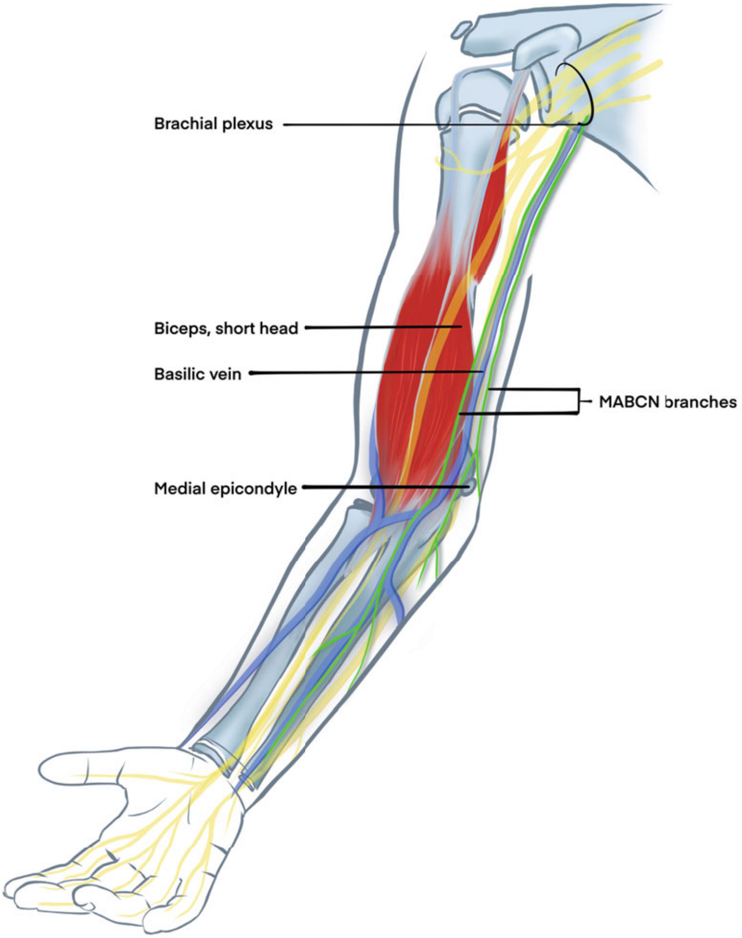


Figure 1. Depiction of an arm with a variant of the course of the Medial antebrachial cutaneous nerves (MABCN) highlighted in green. Note that two branches emerge from the medial cord of the brachial plexus, which run down alongside the basilic vein to provide sensation of the medial forearm.

The medial cutaneous nerves are at risk in open surgery around the medial epicondyle[7], like ulnar nerve release[4, 7, 9, 10] or vascular shunt surgery[5]. In ulnar nerve surgery, previous series described MABCN injury in 50-92% of patients[10, 11]. A high amount of postoperative residual pain may be attributed to the entrapment of small cutaneous nerves or the formation of neurinomas[9, 11].

In elbow arthroscopy, neurological complications have been reported to occur in 0-14% of patients[12, 13]. Branches of the MABCN lie within several millimeters of the proposed introduction site for the (proximal) anteromedial portals[12, 14, 15]. Blunt dissection is advised, but still, traction injury may occur. Even following venipuncture[6, 16] or local injections for epicondylitis[17], MABCN injuries have been reported. Following dissection or traction injury to the MABCN, clinical complaints may include an area of skin numbness[7], pain and lack of elbow extension[9, 11].

The position of the MABCN is traditionally indicated in centimeters compared to anatomical landmarks[18]. However, the surgical procedures and interventions that were summed up previously may be indicated in all age groups and types of patients, with all sorts of body compositions. Therefore, indicating the course of small cutaneous nerves based on their standard distance to anatomical landmarks in centimeters may not be applicable in all patients, like pediatric or obese patients, increasing the risk of nerve injury. This risk may be reduced if surgeons are provided with a depiction of a nerve-free zone at a relative distance to anatomical landmarks that can be applied in any patient regardless of age or body composition.

In Computer Assisted Surgical Anatomy Mapping (CASAM), multiple marked pictures of anatomical specimens can be layered to form one summarizing picture[19, 20]. Individual images are warped into a grid so their landmarks overlay, considering three-dimensional curves. Thus, zones where nerves overlap may be identified, showing in one glance which areas are free of nerves ("safe zones") and which zones contain nerves. CASAM has proved to be valuable in depicting the course of small cutaneous nerves in the wrist[21], around the knee joint[22], and in the lower leg[20].

This study uses CASAM to annihilate the effect of varying body composition and to depict all anatomical variants of the medial cutaneous nerves that are present in ten human specimen in one image. The aim is to assess if there is an area that contains no nerves, which may be used as a potential safe zone for surgical approaches to the medial elbow.

Methods

Ten human arm specimen including the hand and the humeral bone, were used. The specimen were fixed with Anubifix and were positioned in neutral forearm rotation and 90 degrees elbow flexion. Following anatomic dissection of the MABCN, biceps, and vascular structures, AP, LH, and LL then marked nerves, veins, biceps tendon and landmarks for CASAM analysis. The landmarks that were chosen are visible to the surgeon while preparing the patient for surgery. Marker pins were placed in the processus styloideus ulnae (PSU), on the medial epicondyle (ME), in the lesser tubercle on the humeral head (TM) and in the olecranon of the ulna (OL). The elbows were placed in 90 degrees flexion with the lower arm in neutral rotation, simulating the arm's position during elbow arthroscopy or open medial approach to the elbow joint[12, 14].

A line was drawn between the bony landmarks and divided into four to enable the creation of a grid while processing the photographs in CASAM.

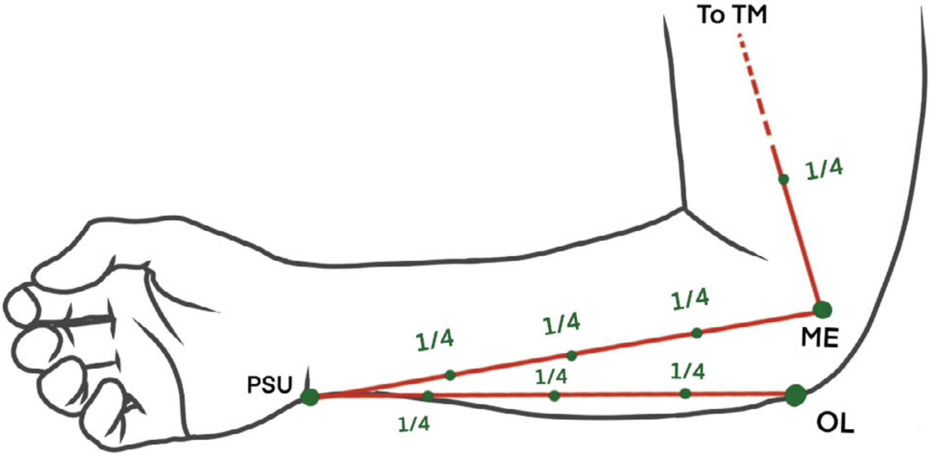


Figure 1. Schematic view of specimen preparation. TM= Tuberculum minus, ME = Medial Epicondyle, PSU = Ulnar Styloid, OL = Olecranon.

A reproducible setup was used for the photography of all arms. A digital camera was used (Nikon D with Sigma 50mm 1:2,8 DG MACRO lens), fixed in a tripod at a 100 cm distance from the specimen. Grid photographs were made before specimen photography to avoid a distortion effect. Photo preparation for CASAM was performed in Photoshop CS4: RAW images were imported and prepared for CASAM analysis.

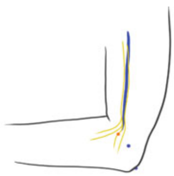
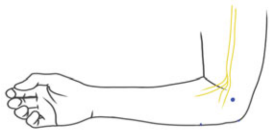
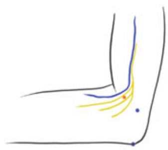
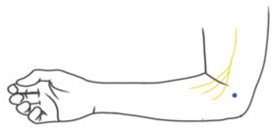
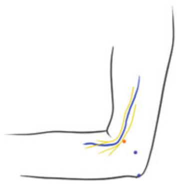
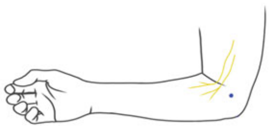
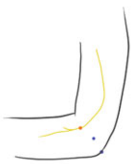
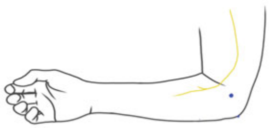
After merging the images into the same elbow contour using MagicMorph software (EffectMatrix Software Studio. Magic Morph 1.95.[23]), a stacked image was obtained that displays the course of all MABCN branches of all specimen in one image. By allowing 10% transparency for the nerves from each specimen, a heat map could be created, showing how often the MABCN was encountered in the same location.

Results

CASAM analysis

The MABCN had multiple branches in most specimen (figure 2). The traditional anteromedial portal for elbow arthroscopy was very close to the MABCN in all cases, even dissecting it in 3/10 cases (orange dot in Figure 2).

A merged figure of all MABCN branches in one image (figure 3) showed a large variation in MABCN distribution: there is no clear zone without cutaneous nerve branches.

	Branches (n) Prox to ME	Branches (n) distal to ME	Graphic image before CASAM	Branch posterior of ME	Image following MagicMorph23
1	2	4		No	
2	1	3		No	
3	2	4		No	
4	1	2		No	

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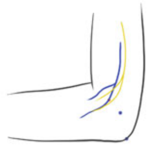
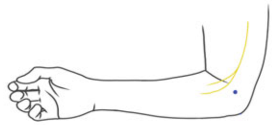
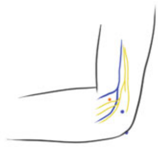
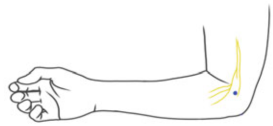
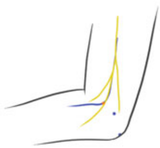
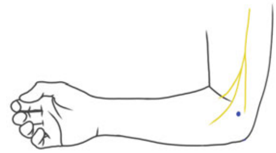
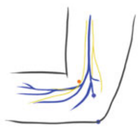
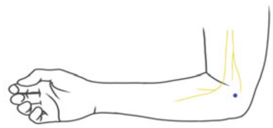
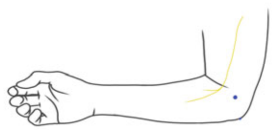
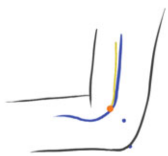
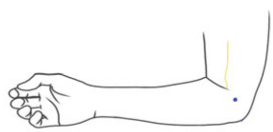
5	1	2		No	
6	3	3		Yes	
7	1	3		Yes	
8	2	2		Yes	
9	1	2		No	
10	1	1		No	
Mean	1.5	2.6		3/10	

Figure 2. Depiction of individual MABCN courses in separate specimen. ME: medial epicondyle. Yellow lines: MABCN branches. Blue lines: Basilic vein. Blue dots: Medial epicondyle and Olecranon tip. Orange dots: traditional anteromedial portal for elbow arthroscopy.

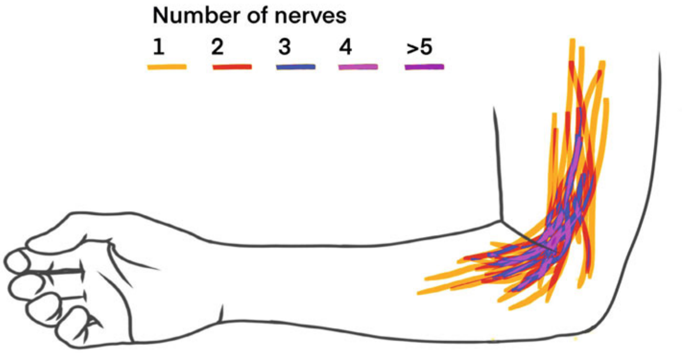


Figure 3. Warped image using CASAM, which annihilates the effect of variations in body composition while respecting three-dimensional relative distances; the MABCN of ten human specimen are depicted overlying each other in one image. No well-defined safe zone could be identified.

Discussion

This study includes a CASAM analysis, which focuses on the branches of the MABCN around the elbow joint, which vary in their number of ramifications and course[2, 4, 11, 18]. It is the first anatomical study that aims to identify the course of the MABCN at relative distances to anatomical landmarks. The aim was to identify a safe zone for surgery to the medial elbow by annihilating the effect of variation in body composition using CASAM.

Our findings, which indicate no definable safe zone for the medial approach to the elbow or ulnar nerve, concur with a study that identified MABCN branches in the surgical wounds of all 97 patients undergoing ulnar nerve decompression[8]. It is essential that awareness of the risk of medial cutaneous nerve injury increases among surgeons.

Complications to cutaneous nerves are described less frequently than complications to larger nerves, such as the radial, ulnar, or median nerve[13]. This may be due to underreporting of these complaints due to injury of smaller nerves[24], especially since they are not registered in commonly used patient-reported outcome measures such as the Oxford Elbow Score or the Mayo Elbow Performance Index. Also, if medial elbow pain due to MABCN injury is misdiagnosed[11], this may contribute to underreporting of these injuries. In a study that described 20 patients with medial pain following ulnar nerve decompression, 65% had a cutaneous nerve neurinoma[9]. Following neuroma resection, the complaints resolved in 8/13 patients.

In conclusion:

This study demonstrates that the MABCN exhibits substantial anatomical variability.

As a result, no consistent safe zone (i.e., no area that contains no nerves) could be identified for surgical approaches to the medial elbow. Surgeons should be aware of the existence and variety of the MABCN and should dissect carefully to identify this nerve and protect it during surgery. Increasing awareness among surgeons is crucial, and further research is required to evaluate the role of cutaneous nerves in (postoperative) elbow pain.

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CHAPTER

03

Computer-Assisted Surgical Anatomical Mapping of the Antebrachial Cutaneous Nerves

An anatomical study with a proposition for alternative, cutaneous nerve-sparing anterior elbow incisions

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Published, JB JS Open Access, 2023 May 15;8(2):e22.00048.
doi: 10.2106/JBJS.OA.22.00048

Abstract

Background It is common practice to assess the distance from nerves to anatomical structures in centimeters, but patients have various body compositions and anatomical variations are common. The purpose of this study was therefore to assess the relative distance from cutaneous nerves around the elbow to surrounding anatomical landmarks by providing a stacked image that displays the average position of cutaneous nerves around the elbow. The aim was to research possibilities for adjusting common skin incisions in the anterior elbow so that cutaneous nerve injury may be avoided.

Methods The lateral antebrachial cutaneous nerve (LABCN) and medial antebrachial cutaneous nerve (MABCN) were identified in the coronal plane around the elbow joint in 10 fresh-frozen human arm specimens. Marked photographs of the specimens were analyzed using computer-assisted surgical anatomical mapping (CASAM). Common anterior surgical approaches to the elbow joint and the distal humerus were then compared with merged images, and nerve-sparing alternatives are proposed.

Results The arm was divided longitudinally, from medial to lateral in the coronal plane, into 4 quarters. The LABCN crossed the central-lateral quarter of the interepicondylar line (i.e., was somewhat lateral to the midline at the level of the elbow crease) in 9 of 10 specimens. The MABCN ran medial to the basilic vein and crossed the most medial quarter of the interepicondylar line. Thus, 2 of the quarters were either free of cutaneous nerves (the most lateral quarter) or contained a distal cutaneous branch in only 1 of 10 specimens (the central-medial quarter).

Conclusions The Boyd-Anderson approach, which is often used to access anteromedial structures of the elbow, should be placed slightly further medially than traditionally advised. The distal part of the Henry approach should deviate laterally, so that it runs over the mobile wad. In distal biceps tendon surgery, the risk of cutaneous nerve injury may be reduced if a single distal incision is placed slightly more laterally (in the most lateral quarter), as in the modified Henry approach. If proximal extension is required, LABCN injury may be prevented by using the modified Boyd-Anderson incision, which runs in the central-medial quarter.

Clinical Relevance: Cutaneous nerve injury may be prevented by slightly altering the commonly used skin incisions around the elbow on the basis of the safe zones that were identified by depicting the cumulative course of the MABCN and LABCN using CASAM.

1 2 3 4 5 6 7 8 9 10 AI AII AIII AIV AV AVI AVII AVIII

Introduction

The courses of the cutaneous nerves around the elbow are known to vary among individuals[1,2]. These nerves are at risk for sharp dissection or traction neurapraxia during surgical procedures. Painful neuromas may form, and elbow range of motion may even be affected[3,4]. The lateral antebrachial cutaneous nerve (LABCN) is a superficial terminal branch of the musculocutaneous nerve that emerges from underneath the lateral side of the biceps tendon. It is responsible for the sensory innervation of the lateral radial side of the forearm[5]. The medial antebrachial cutaneous nerve (MABCN) emerges from the brachialis fascia[2] and runs medial to the basilic vein at the level of the medial epicondyle[6]. These cutaneous nerves are at risk for transection or neurapraxia due to traction in several surgical procedures.

It would therefore be useful to identify a "safe zone" free of cutaneous nerve branches that can be utilized to reduce the risk of iatrogenic cutaneous nerve injury. Several previous studies have described the distance between the nerves and anatomical landmarks in centimeters[2,7],whichmay not be accurate for patients with different body compositions. A cohort study of patients who underwent distal biceps tendon repair identified obesity as a risk factor for postoperative LABCN neurapraxia because anatomical exposure and protection of this delicate cutaneous nerve were complicated by the subcutaneous tissue8. It would therefore be very useful to provide surgeons with a map of safe zones that are based on the relative distance to anatomical landmarks, rather than the absolute distance in centimeters, and can therefore be applied to any patient. Computer-assisted surgical anatomical mapping (CASAM) merges multiple 2-dimensional photographs into a single image and takes 3-dimensional structures into account[9,10]. It has proven to be a reliable technique for depicting the course of small cutaneous nerves around the wrist[11], knee[12], and lower leg[9].Warping marked pictures of anatomical specimens allows the relative distance from anatomical structures to landmarks to be assessed, and safe zones with the least likelihood of containing superficial nerves may be identified. The present study used CASAM to depict the variable courses of the LABCN and MABCN in the coronal plane around the elbow joint. The goal was to merge several images of human specimens and depict the relative distances from the nerves to several landmarks around the elbow joint in a heat map that may be applied to any individual patient, and then identify potential safe zones for surgical approaches to the elbow joint and the distal humerus. Two optimizations of traditional approaches to the anterior distal humerus will be proposed, and options for incisions used in distal biceps ten don surgery will be discussed.

Materials and methods

Ten human arm specimens that included the hand and the humeral bone were fixed using AnubiFiX. Anatomical preparation was performed by 2 authors (A.R.P. and L.H.), and 2 authors (A.R.P. and L.C.L.) then marked nerves, veins, the biceps tendon, and landmarks for CASAM analysis. We chose to use landmarks that are visible to the surgeon while preparing the patient for surgery. Markers were placed on the lateral epicondyle (LE), radial styloid (RS), and lesser tuberosity of the humerus (tuberculum minus, TM). The elbows were extended with the lower arm supinated, as the patient would be positioned for reconstruction of the distal biceps tendon (Fig. 1). Lines were drawn between the osseous landmarks and divided into equal proportions (green dots in Fig. 1) to allow creation of a grid during processing of the photographs in CASAM. The grid allows the program to respect curves and relief when building a 3 dimensional surface model[9].

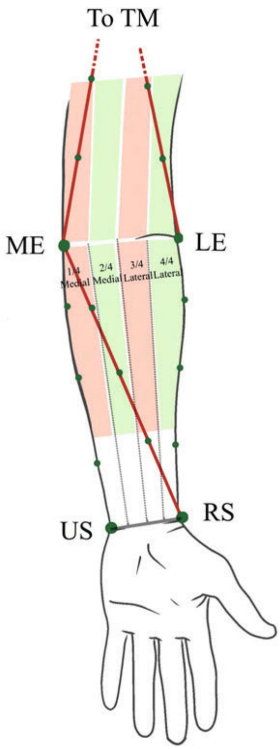


Figure 1. Schematic view of a specimen. Each specimen was photographed in the coronal plane in full supination. The arm was then divided into 4 quarters (red and green areas) by dividing the line between the radial styloid (RS) and ulnar styloid (US), the interepicondylar line (between the medial epicondyle [ME] and the lateral epicondyle [LE]), and the proximal end of the specimen into quarters. Dark green dots and red lines indicate markers that were placed to enable grid formation in Magic Morph. TM = tuberculum minus.

A reproducible setup was used for photographing all arms. A digital camera (NikonDwithSigma50mm1:2.8DGMACRO lens) was fixed on a tripod at a distance of 100 cm from the specimen. Test photographs of a checkered surface were made prior to specimen photography to confirm that there was no distortion effect. Three-dimensional warping was performed using Magic Morph (version 1.95; EffectMatrix), and image analysis was performed in Photoshop CS4 (Adobe). First, the courses of the LABCN, MABCN, nearby veins such as the medial antebrachial vein and the cubital vein, and the distal biceps tendon in each image were drawn onto the image in a separate layer using a digital stylus pen (Figs. 2-A and 2-B).

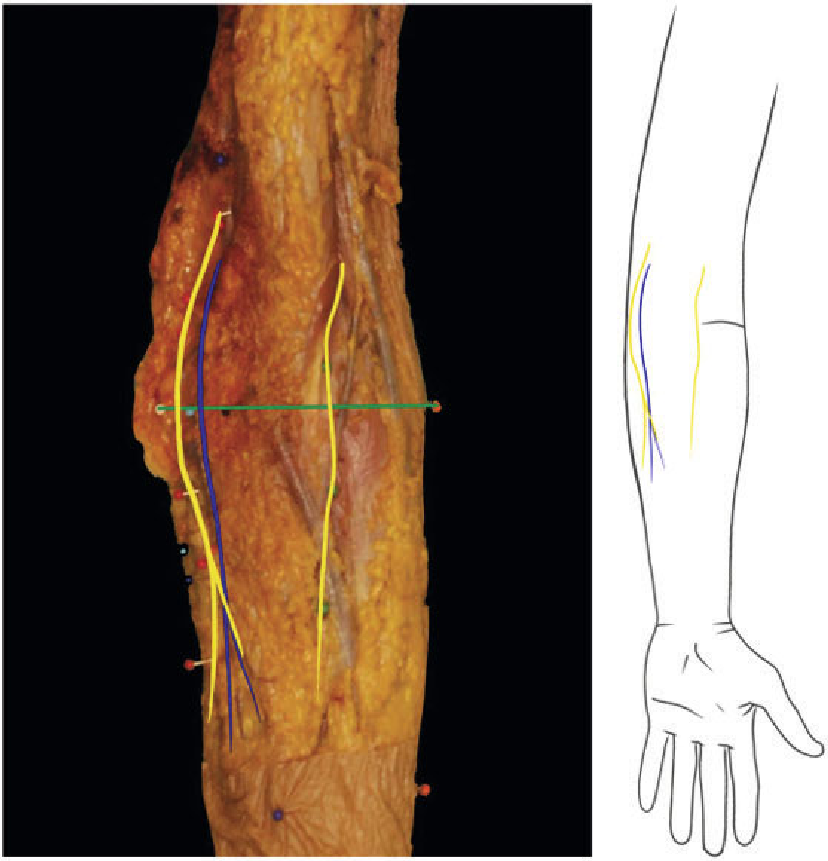


Fig. 2-A Fig. 2-B

Fig. 2-A Photograph showing a representative specimen. The MABCN is indicated with red pins, and the LABCN is indicated with green pins. The green line is the interepicondylar line. The yellow lines indicate the LABCN and MABCN, and the blue line indicates the basilic vein. **Fig. 2-B.** Digital depiction of the LABCN and MABCN of the same specimen after the image has been warped using MagicMorph. The MABCN was found to run medial to the basilic vein in all specimens.

The 10 individual images containing an exact copy of the nerves were then stacked, and these layers were combined into a single heat map presenting an overview of anatomical structures (Fig. 3-A). The arm was divided longitudinally, from medial to lateral in the coronal plane, into 4 quarters as shown in Figure 1, and the positions of the nerves were assessed at the level of the elbow crease (as they crossed the interepicondylar line, a line connecting the medial and lateral epicondyles).

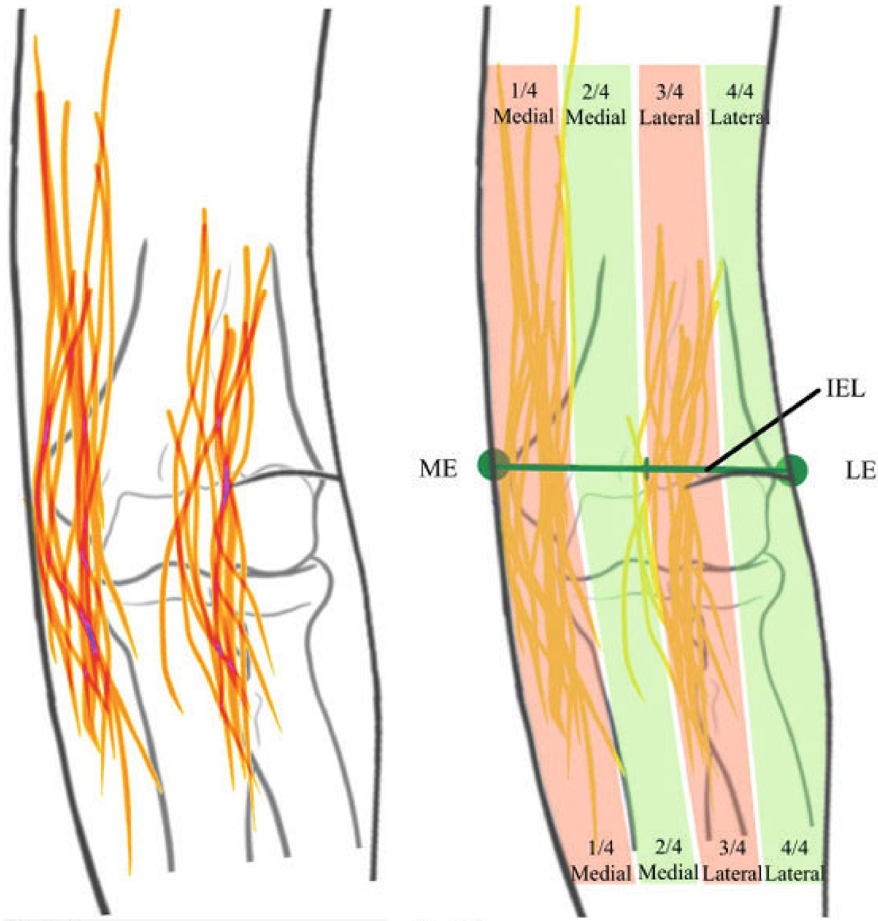


Fig. 3-A Fig. 3-B

Fig. 3-A. Heat map showing the LABCN and MABCN positions in a coronal view of a right elbow. Yellow indicates 1 nerve; orange, 2 overlapping nerves; red, 3 overlapping nerves; and blue, 4 overlapping nerves. Nine of the 10 LABCNs can be seen to cross the elbow crease lateral to the midline. **Fig.3-B**. Coronal view showing a right elbow divided into 4 quarters. Relative safe zones can be seen in the central-medial(2/4) quarter and in the most lateral (4/4) quarter. As in Figure 1, the green line is the interepicondylar line (IEL) connecting the lateral epicondyle (LE) and medial epicondyle (ME).

Results

The LABCN and MABCN could be identified in all 10 specimens (Figs. 3-A and 3-B). The LABCN originated from underneath the lateral distal biceps tendon in all specimens, and it bifurcated distal to the elbow crease in 2 specimens. A pattern could be seen in which the course of the LABCN was lateral to the medial cubital vein proximally and medial to the cephalic vein distally.

The LABCN crossed lateral to the midpoint of the interepicondylar line in 9 of the 10 specimens. The MABCN ran medial to the basilic vein and crossed the most medial quarter of the interepicondylar line in all specimens. Figure 3-A shows the merging of all specimens into a single file using CASAM. A safe zone can be seen in the most lateral quarter at the level of the elbow crease, and a relatively safe zone can be seen in the central-medial quarter, as shown in Figure 3-B.

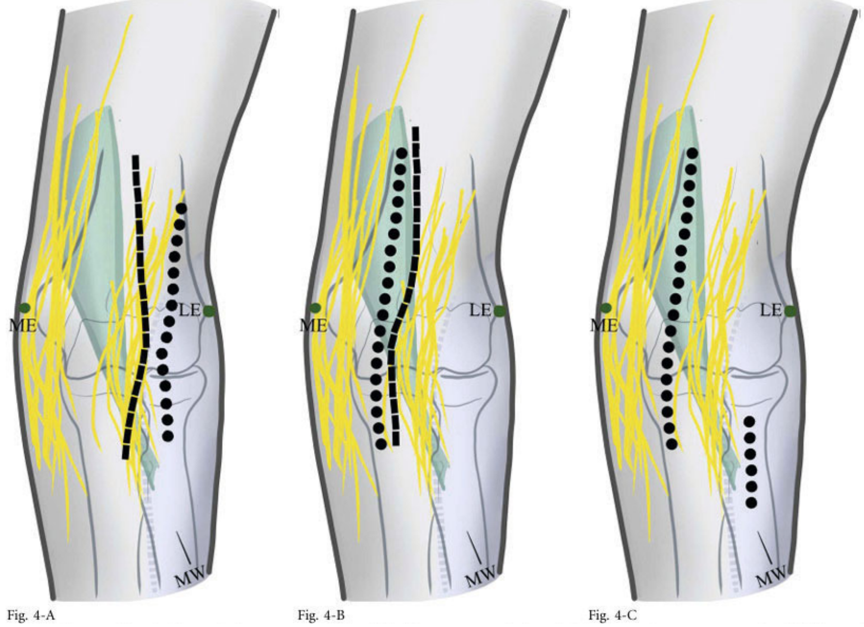
Discussion

This study focused on the small cutaneous nerves around the elbow and used CASAM to analyze their courses in 10 human specimens. The results indicate that subtly shifting the commonly used skin incisions by several millimeters may reduce the risk of damaging the small cutaneous nerves surrounding the elbow. Deeper dissection, below the subcutaneous fat, remains unaltered.

Henry Anterior Distal Humeral Approach

The Henry approach uses the “mobile wad” (MW in Fig. 4-A) as a landmark. The mobile wad is a palpable mobile muscle mass, formed by the extensor muscles of the wrist and hand, on the proximal lateral side of the lower arm. The skin incision then progresses proximally along the lateral border of the biceps tendon and muscle—”a slender fingerbreadth lateral to the edge of the biceps,” as Henry stated. There is a high risk of incising or placing traction on the LABCN[13] (Fig. 4-A). In a retrospective study, numbness, tingling, or pain around the scar was reported by 62% of 40 patients following surgery using an anterolateral Henry approach to the humerus[14]. Henry, too, acknowledged that “surgeons will take a pride in rescuing the lateral cutaneous twig of musculocutaneous which runs in surface fat.”[13] The Henry approach may be modified to prevent LABCN injury by deviating the distal part of the skin incision laterally, over the mobile wad. After starting proximally and running lateral to the lateral border of the biceps muscle, it should deviate laterally when crossing the elbow crease (Fig. 4-A).

The internervous plane between the brachialis and brachioradialis muscles should still be reachable if the lateral deviation is not commenced too proximally. This incision may be advantageous in approaching complex fractures of the capitellum or trochlea of the distal humerus[15].



Figs. 4-A, **4-B**, and **4-C**. Approaches to the anterior aspects of the distal humerus and elbow joint. The cutaneous nerves in all 10 specimens (yellow) have been merged into 1 image. Traditional approaches are shown by dashed lines, and proposed nerve-sparing alternative skin incisions are shown by dotted lines. LE = lateral epicondyle, ME = medial epicondyle, and MW (gray dashed line) = mobile wad. **Fig. 4-A**. The Henry approach runs between the MW and the lateral border of the distal biceps (green)[13,21]. The alternative runs slightly further laterally and curves laterally, over the mobile wad. **Fig. 4-B** The Boyd-Anderson approach[17] starts proximal and lateral to the biceps muscle, crosses the elbow crease at a non-perpendicular angle, and extends to the medial border of the biceps tendon. The alternative runs slightly further medially, but lateral to the basilic vein distally. **Fig. 4-C.** Alternative incisions for distal biceps repair. If an extensive incision is needed, it should follow the same course as in Figure 4-B. If only a distal incision is used, it should lie further laterally.

Boyd-Anderson Anterior Distal Humeral Approach

The LABCN is encountered between the brachialis muscle and the distal biceps tendon[16] in the traditional anterior Boyd Anderson approach to the distal humerus[17]. The s-shaped skin incision that is made to access the anterior aspect of the humerus may be extended distally and medially to approach the coronoid, Lacertus fibrosus, and median nerve (Fig. 4-B). The risk of encountering a cutaneous nerve is high, especially around the elbow crease. A modified Boyd-Anderson approach should ideally be placed slightly further medially (Fig. 4-B). Medial structures such as the coronoid, Lacertus fibrosus, median nerve, and medial side of the distal humerus may be reached by an incision that starts proximally over the biceps muscle and deviates medially when crossing the elbow crease. Distally, the incision should not cross the basilic vein, to prevent injury to the MABCN. This advice is in agreement with the findings of King and Johnston[14], who stated that the anterior approach to the distal humerus should use an incision located slightly more medially than in the traditional Henry approach.

Distal Biceps Tendon Repair

The most common complication in distal biceps tendon repair is injury to the LABCN, with reported rates of 9.2% to 30%[1,18,19]. Several options for approaching the footprint of the distal biceps on the radial tuberosity have been described. A single distal incision may start 2 fingerbreadths distal to the elbow crease[18], and it may be transverse or run longitudinally along the medial border of the mobile wad[20]. In a recent review, the rate of LABCN injury was significantly higher with an extensive approach that crossed the elbow crease proximally than with a limited anterior approach that only involved a distal incision. Transient neurapraxia was frequent, which may be attributed to traction on the nerve[1]. Based on the CASAM analysis of the LABCN in the present study, we propose slightly modified approaches. If there is no need to extend the exposure proximally, a single distal incision should be placed slightly further laterally, as in the modified Henry approach described above.

The traditional interval between the brachioradialis and pronator teres muscles may be accessed through this modified incision. We advise against a transverse incision, as the risk of cutaneous nerve damage is high and there is no option to extend the incision if visualization of anatomical structures is insufficient. If the exposure needs to be extended proximally, as maybe the case if the tendon is retracted in a chronic injury, a single extensive Boyd-Anderson incision may be placed slightly further medially (Fig. 4-B), taking caution not to cross the basilic vein.

Conclusions

The cutaneous nerves around the elbow are at risk in several surgical procedures that involve exposure of the anterior humerus, elbow joint, or distal biceps tendon. CASAM analysis of the courses of these nerves illustrated that the LABCN ran somewhat lateral to the midline of the lower arm at the level of the elbow crease in 9 of 10 specimens. The central-medial quarter and the most lateral quarter of the arm in the coronal plane were both relatively safe, with no or almost no cutaneous nerve branches in the specimens.

We propose slight modifications to the skin incisions that are traditionally used to expose the elbow joint and distal humerus, in order to decrease the risk of cutaneous nerve injury. Deeper dissection can then proceed in the same manner as following the traditional incisions. The incision for the Boyd-Anderson approach should be placed slightly further medially than traditionally advised. The distal part of the incision for the Henry approach should deviate laterally, so that it runs over the mobile wad. The distal part of the incision for distal biceps tendon surgery should be longitudinal and slightly lateral to the border of the mobile wad.

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PART TWO

2

Outcome following paediatric radial neck fracture

CHAPTER 04

The Presence of Associated Injuries in Pediatric Radial Neck Fractures:

A Systematic Review of the Literature and Meta-Analysis of Pooled Individual Patient Data

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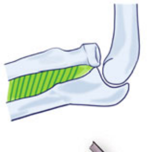
Publised, Children (Basel), 2025 Feb 27;12(3):300.
doi: 10.3390/children12030300.



Abstract

Background Pediatric radial neck fractures (pRNFs) can occur in isolation or in association with concomitant injuries. It is unknown whether the presence of associated injuries should influence the choice of treatment. The aim of this study is to assess the incidence of associated injuries in pRNF and their correlation with fracture angulation (Judet grade) or the patient's age (under or over ten years of age).

Methods A systematic literature review was performed following PRISMA-IPD guidelines, including case series on pRNF with a minimum of five cases of children until 16 years of age. The quality assessment included a risk of bias analysis and evaluation using the MINORS criteria. Individual patient data on age, Judet classification and associated injuries were extracted from the included studies and pooled for the meta-analysis. The correlation between the presence of associated injury and the patient's age or Judet classification was depicted in two forest plots.

Results A total of 20 articles published sufficient individual patient data (n = 371) on associated injuries. All but one were retrospective case series. Fifteen articles had MINORS scores of 8 or higher. The incidence of associated injuries was 33% (123 of 371 cases). Almost half of the associated injuries included an olecranon fracture (61/123). There was no correlation between Judet classification (p = 0.243) and incidence nor between patient age and the incidence of associated injuries (p = 0.694).

Conclusions Surgeons should be aware of potential associated injuries in over a third of pRNF cases, regardless of the patient's age or fracture angulation. Deduction of the trauma mechanism may be a more useful tool for assessing the potential presence of associated injuries than the most frequently used fracture classification or the patient's age. More research is needed regarding the requirements for enhanced diagnostic imaging, specific treatment or follow-up adaptations in children with pRNFs and associated injuries.

Keywords: pediatric trauma; radial neck fracture; radial neck trauma; elbow injury

1 2 3 4 5 6 7 8 9 10 AI AII AIII AIV AV AVI AVII AVIII

Introduction

Radial neck fractures in children have been evaluated and treated for almost a century [1, 2]. However, the criteria for the treatment choice remain a topic of debate. Numerous studies have reviewed the acceptable angulation of the radial neck and the related threshold for surgical intervention [3, 4]. To date, it is still uncertain how the choice of treatment in pediatric radial neck fractures (pRNFs) should be altered if there are concomitant fractures or soft tissue injuries around the affected elbow. Case series and even reviews that have included associated injuries in their analyses report miscellaneous effects of associated injuries on the long-term outcome of pRNFs [4].

Because multiple ossification centers around the joint appear at different ages, diagnosing associated injuries in RNFs is even more complex in children [5, 6]. In the literature, there is speculation that younger children are more prone to experiencing fractures as opposed to avulsion injuries due to the cartilaginous tissue in the physes [7]. Also, the type of avulsions or fractures that may be seen is susceptible to age [7-9]. Several authors report higher complication rates and unsatisfying outcomes in patients over ten years of age [10-12]. However, the impact of patient age on the incidence and type of associated injuries in pRNFs has never been studied.

In theory, a pRNF that is part of a more complex injury will require a different treatment from that for an isolated radial neck injury [11, 13] because the presence of associated injuries may reflect a higher-energy trauma [11, 14-17]. However, the most frequently used pRNF classifications are only based on radiologic criteria which do not include injuries to the surrounding ligaments or bones (Judet, [1], O'Brien [18] and AO Surgery [19, 20], and some even include an overlap with those for intraarticular radial head lesions (Mason classification [21]). The current classification systems, such as the Judet grades, fail to address associated injuries, limiting their utility in guiding treatment. Even though it is presumed that higher fracture grades include a higher risk of associated injuries [4, 22-24], there has never been an evaluation of the correlation between fracture angulation and the occurrence of associated injuries.

This study aims to provide a review of the literature and bridge this gap by analyzing the incidence and implications of associated injuries in pRNFs. The first aim is to evaluate whether there is a correlation between the incidence of associated injuries and patient age or Judet classification. Secondly, it aims to assess whether specific injuries are more prevalent in certain groups of patients based on Judet classification or age.

Materials and Methods

Systematic Search

This study followed the guidelines of the Preferred Reporting Items for Systematic reviews and Meta-analyses of Individual Patient Data (PRISMA-IPD [25]). Before starting the review process, the review was registered in PROSPERO (CRD42024572829). A systematic search was performed in Medline, Embase, Web of Science's core collection, Cochrane Central Register of Controlled Trials and Google Scholar (Figure 1) in March 2024. Two separate reviewers (L.C.L. and N.B.B.) included case series with over 5 children that published sufficient data on the fracture (associated injuries, Judet classification) and patient age. The inclusion criteria were children $<$ 16 years old with acute radial neck fractures. C.J.A.v.B. reviewed studies with a conflicting inclusion judgment as a third reviewer.

If solely group data were published without details on the individual patients, authors were contacted with a request to supply additional information via email. In cases without a response, these papers were excluded from the incidence analysis because no correction of the confounding factors was possible. Examples were as follows: selection bias in publications of non-consecutive cases, the publication of a select group of patients (only surgically treated cases, specific trauma mechanism or age group), etc.

Individual Patient Data Analysis: Associated Injury Incidence

Individual patient data on Judet grade and patient age were used for the meta-analysis. Three categories of initial fracture angulation were created based on the Judet grade: Judet 1 or 2 (fracture angulation of under 30 degrees), Judet 3 (fracture angulation of 30–60 degrees) and Judet 4 (fracture angulation of over 60 degrees).

Based on the previous literature that assumes a different injury mechanism over the age of ten [7-9], two age groups were created for children below and over the age of ten years to assess the influence of patient age on the occurrence of associated injuries.

Statistical Analysis

A statistical analysis was performed in R (Rstudio version 2024.04.2). An epidemiologic overview of the occurrence of associated injury was performed, identifying the most common lesions besides the radial neck fracture. A proportion meta-analysis explored the incidence of associated injuries with a random-effects model to determine whether subgroups of Judet classification or patient age showed different incidences. Forest plots were used to depict the correlation between the Judet classification or patient age and the presence of associated injury.

All of the tests were two-sided, and the significance of the statistical differences was attributed to a p-value of <0.05.

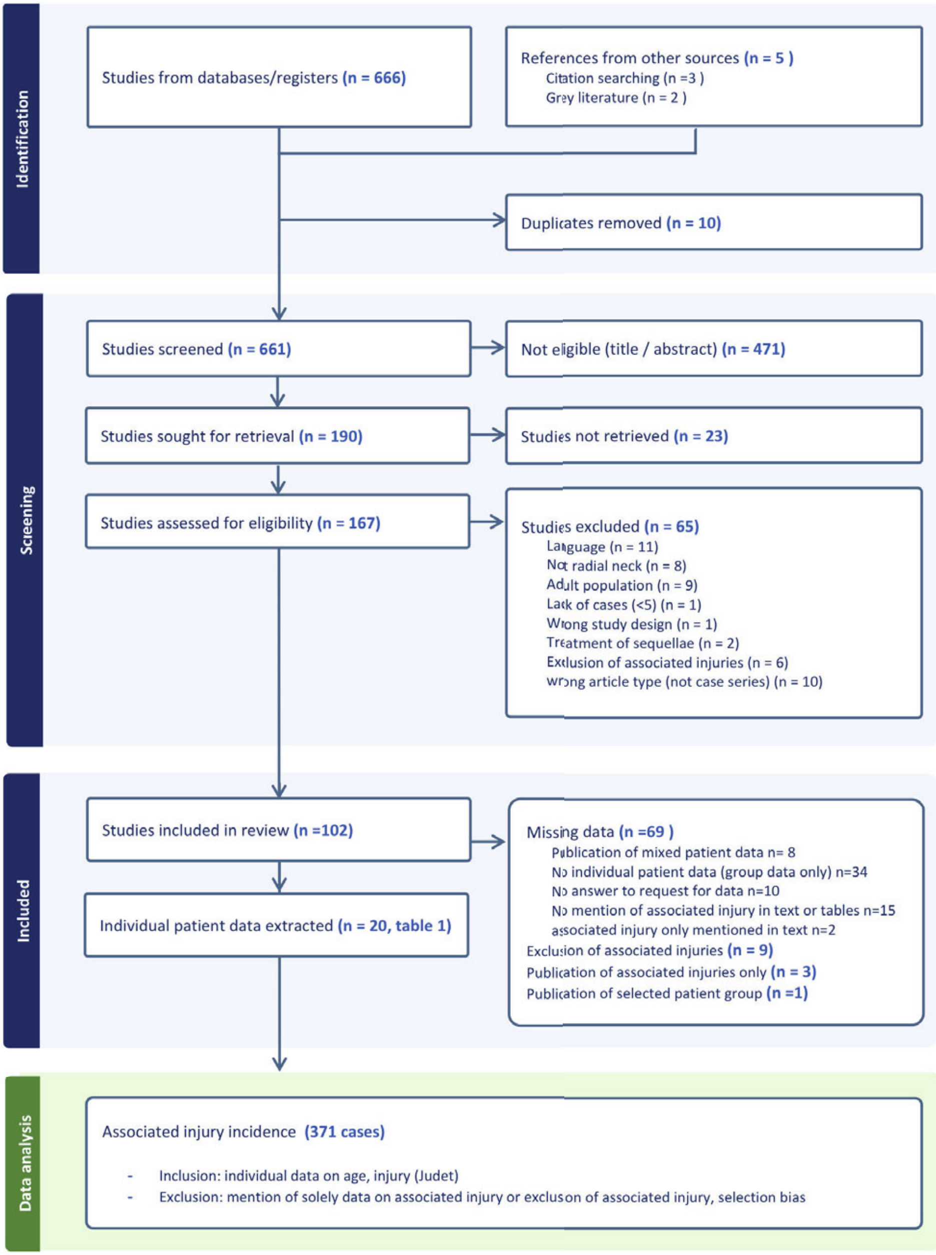


Figure 1. PRISMA-IPD guided search and specification of the inclusion of individual patient data for the analysis of the incidence of associated injuries (green rectangle). Mixed data: pRNF data published mixed with intraarticular fractures or data from adults (Mason classification was used).

Results

Systematic Search

Following the title and abstract screening, 190 articles were sought for retrieval (Figure 1). Most of the studies that could not be retrieved had been published before 1980. A total of 102 case series were read and screened for eligibility for individual patient data extraction. Several of these case series solely presented group data (n = 34), which did not allow for an analysis of individual patient data. Thereby, ten case series were excluded because they did present some individual patient data but not all of the required inclusion criteria were met. The authors of these series were contacted by email with a request for the data. All ten were subsequently excluded because no reply was received. The IPD's integrity was high; most of the case series published the same patient characteristics, even though some series dated before 2000. A quality assessment was performed using an adapted version of the MINORS criteria, mostly because all but one [26] of the case series were retrospective cohort studies (Table 1).

Analysis of the Incidence of Associated Injuries

Several case series could not be used for the incidence analysis because inclusion bias applied. Nine authors mentioned the exclusion of multiple fractures or associated injuries [4, 44-51]. Only one [52] indicated that the incidence of associated injuries was 34% amongst operated patients; two mentioned associated injuries in the text but did not indicate in which patients these occurred in the table of patient data [53, 54]. Three case series contained associated injuries solely and could therefore not be included in the incidence analysis [11, 55, 56]. Fifteen articles did not mention whether associated injuries were present and were therefore excluded [57-70]. Eventually, 20 articles could be used for the analysis of the incidence of associated injuries in pRNFs (Table 1).

The incidence of associated injuries could be evaluated in individual patient data from 371 patients. Of these children, 123 had an associated injury (33.15%). There were 57 olecranon fractures, and an additional 4 olecranon fractures were part of an elbow dislocation. The second most frequent associated injury was an ulna fracture (other than olecranon; 14 cases; Table 2, Figure 2).

In both age groups, olecranon fractuEes were the most commonly associated injuries. Especially in very young children (<6 years, n = 37), olecranon fractures were diagnosed frequently (10/13 associated injuries in children < 7 years). Elbow dislocations were present more frequently in older children (3/205 in children under ten (1.5%) vs. 13/166 in children over ten (7.8%, CHI^2 $p = 0.003$). The youngest child who had a dislocation was 7 years old.

Table 1. Overview of the included case series, including MINORS scores.

Author	Year	Inclusion Range	Study Population	n	IPD Total	n AsInj	IPD AsInj	% AsInj	MINORS 1	2	3	4: Outcome Scales	5	6	7	Total Score
Al Aubadi [27]	2012	2004–2008	displaced pRNF, treated with Metaizeau	16	16	5	5	31.25	1	1	2	Metaizeau, DASH, Steele	2	2	0	8
Baghdadi [28]	2021	2009–2018	pRNF that had OR	22	21	9	8	40.91	1	2	2	Flynn criteria, radiologic outcome	1	2	2	10
Bilal [29]	2021	2012–2014	pRNF > 30 gr, which could be managed using clamp leverage	15	15	3	3	20.00	1	1	1	Metaizeau radiologic criteria	2	0	2	7
Cevik [30]	2018	2007–2014	pRNF J3/4, CIMP + pKw leverage	20	20	4	4	20.00	1	2	2	Ursei, Tibone–Stoltz	2	0	2	9
Cha [31]	2012	2006–2008	pRNF treated with CIMP	13	13	4	4	30.77	2	1	2	Steele, ROM, radiologic criteria	2	0	0	7
Endele [32]	2010	1993–2006	pRNF treated with CIMP	54	42	21	17	38.89	1	1	2	Morrey and Metaizeau score	2	2	2	10
Falciglia [33]	2014	2000–2009	pRNF with OR after CR failed	24	24	4	4	16.67	1	1	1	ROM, own classification	2	0	2	7
Fowles [22]	1986	1965–1980	all pRNF	23	19	14	11	60.87	2	1	2	ROM, axis, radiological criteria	2	1	2	10
Guyonnet [34]	2017	2010–2015	pRNF treated with CIMP	24	24	4	4	16.67	1	2	2	Quick-DASH	1	0	2	8
Jones [35]	1971	1955–1969	displaced pRNF	34	34	10	10	29.41	1	1	2	ROM	2	2	2	10
Kashayi [36]	2022	2003–2009	pRNF treated with pKw leverage by one surgeon	9	9	5	5	55.56	1	2	2	ROM, MEPS	1	0	2	8
Kim [37]	2023	2012–2021	displaced pRNF	37	37	9	9	24.32	1	1	2	MEPS, Tibone–Stoltz	2	0	2	8
Lu [38]	2023	2015–2021	pRNF with medial epicondylar fracture	12	12	6	6	50.00	1	1	2	MEPS, ROM, carrying angle	2	0	2	8
Monson [39]	2009	nd	displaced pRNF	6	6	6	6	100.00	0	1	1	radiological RN reduction	0	0	0	2
Pesudo [40]	1982	nd	proximal radial epiphysis fractures	10	10	2	2	20.00	1	0	1	radiological criteria	2	0	2	6
Shah [41]	2021	2017–2018	completely displaced pRNF	10	10	1	1	10.00	2	1	1	ROM, radiologic union	2	0	0	6
Stiefel [10]	2001	1994–1996	J4 pRNF	6	6	2	2	33.33	2	1	2	own classification	1	0	0	6
Takeda [42]	2022	2005–2013	surgically treated pRNF	10	10	5	5	50.00	0	1	2	Leung/Peterson	2	0	2	7
Vocke [26]	2000	1984–1994	all pRNFs	38	38	16	16	42.11	1	1	1	ROM, complications	2	1	2	8
Walcher [43]	2000	1993–1996	displaced pRNF	5	5	1	1	20.00	1	1	1	G/P without further explanation, ROM	1	0	1	5
				388	371	224	123	33.15								

n: number of cases. IPD: individual patient data. Baghdadi, Fowles and Endele included cases with missing data, hence the difference in the total n and extracted IPD. As inj: associated injury. MINORS 1: Consecutive cases (1: patient selection process described in text; 2: consecutive cases). 2: Clear aim (1: aim stated but no clear outcome measures; 2: aim and outcome measures clearly stated). 3: Unbiased evaluation (0: subject to bias; 1: outcome measures may be subject to slight bias, like ROM or patient opinions on result; 2: clear outcome measures). 4: Outcome scales. 5: Follow-up published (1: group follow-up, 2: IPD of follow-up available). 6: Lost to follow-up (0: not mentioned; 1: mentioned without IPD of lost patients; 2: IPD of lost patients available).

Table 2. Incidence of associated injuries in 371 individual cases. MCL: medial collateral ligament.

Overview of the Incidence of Associated Injuries, n = 371			
Associated Injuries		**Age <10 y n = 205**	**Age > 10 y n = 166**
Olecranon fracture	53	37	16
including wrist drop	1	1	
including lateral condyle fracture	2	1	1
including ipsilateral distal radius fracture	1		1
Ulna fracture	14	8	6
Medial epicondyle fracture or avulsion	8	1	7
Including lateral epicondyle fracture	1		1
Lateral epicondyle fracture	1		1
Monteggia injury	3	3	
Radius and ulna fracture	3	1	2
Ipsilateral distal radius fracture	2	1	1
Coronoid fracture	1		1
Ipsilateral radial head	1		1
"Multiple"	1		1
Elbow dislocation	16	3	13
including olecranon fracture	4	4	
including medial condyle fracture	1		1
including MCL tear	1		1
terrible triad	1	1	
Ligament injuries			
Ulnar collateral ligament injury	4	4	
Lateral collateral ligament injury	1		1
Cubitus valgus	1		1
Neurologic injuries			
Wrist drop	1	1	
Ulnar nerve injury	1	1	
TOTAL	**123**	**67**	**56**

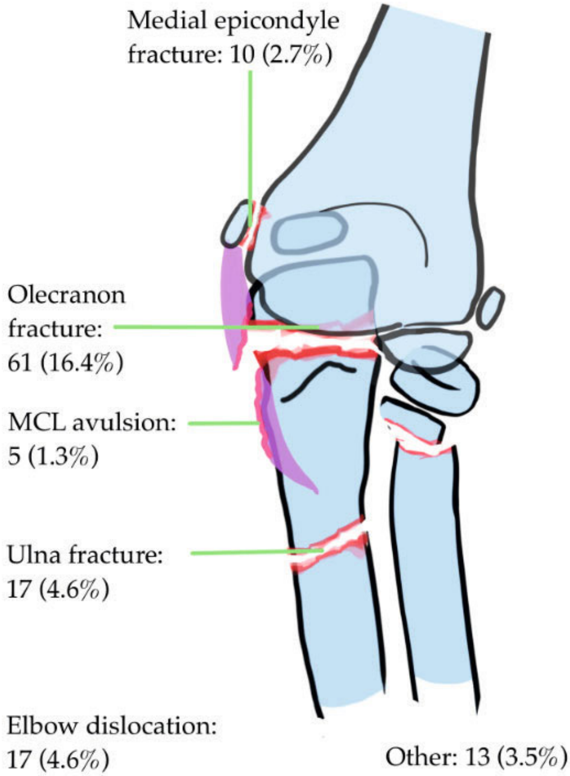
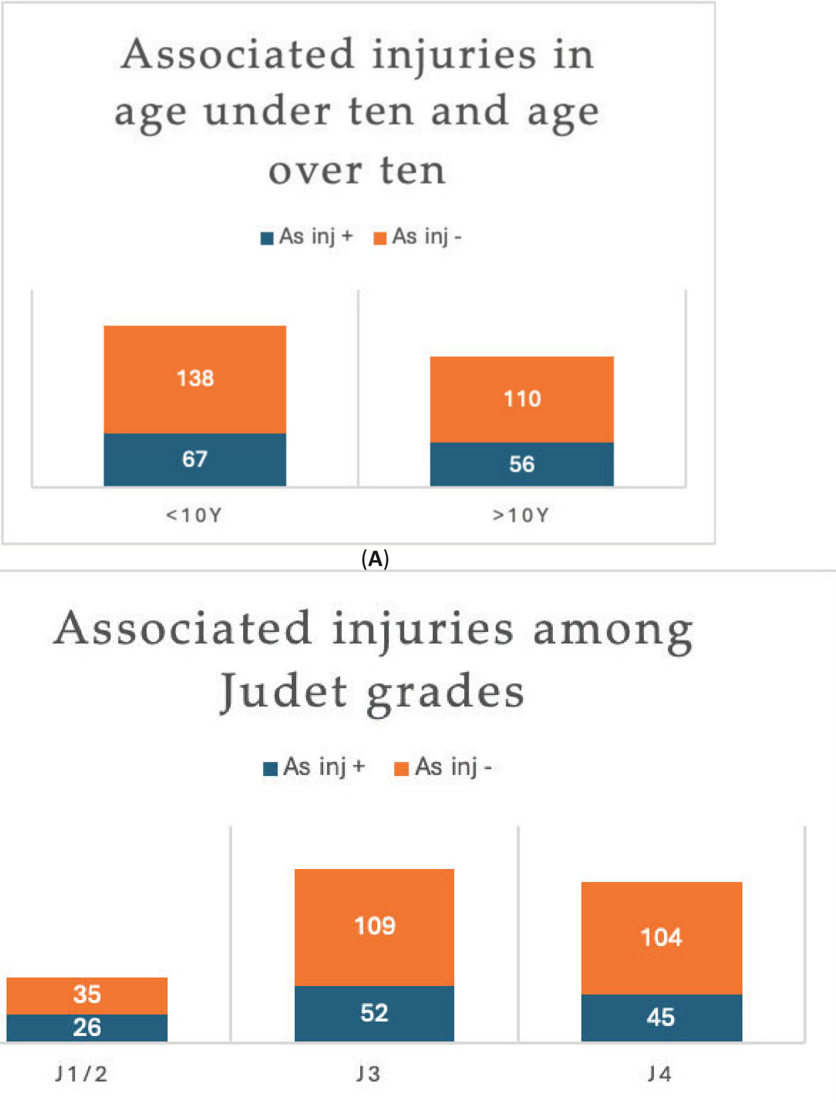


Figure 2. The incidence of associated injuries in pediatric radial neck fractures in a pooled analysis of 371 cases.

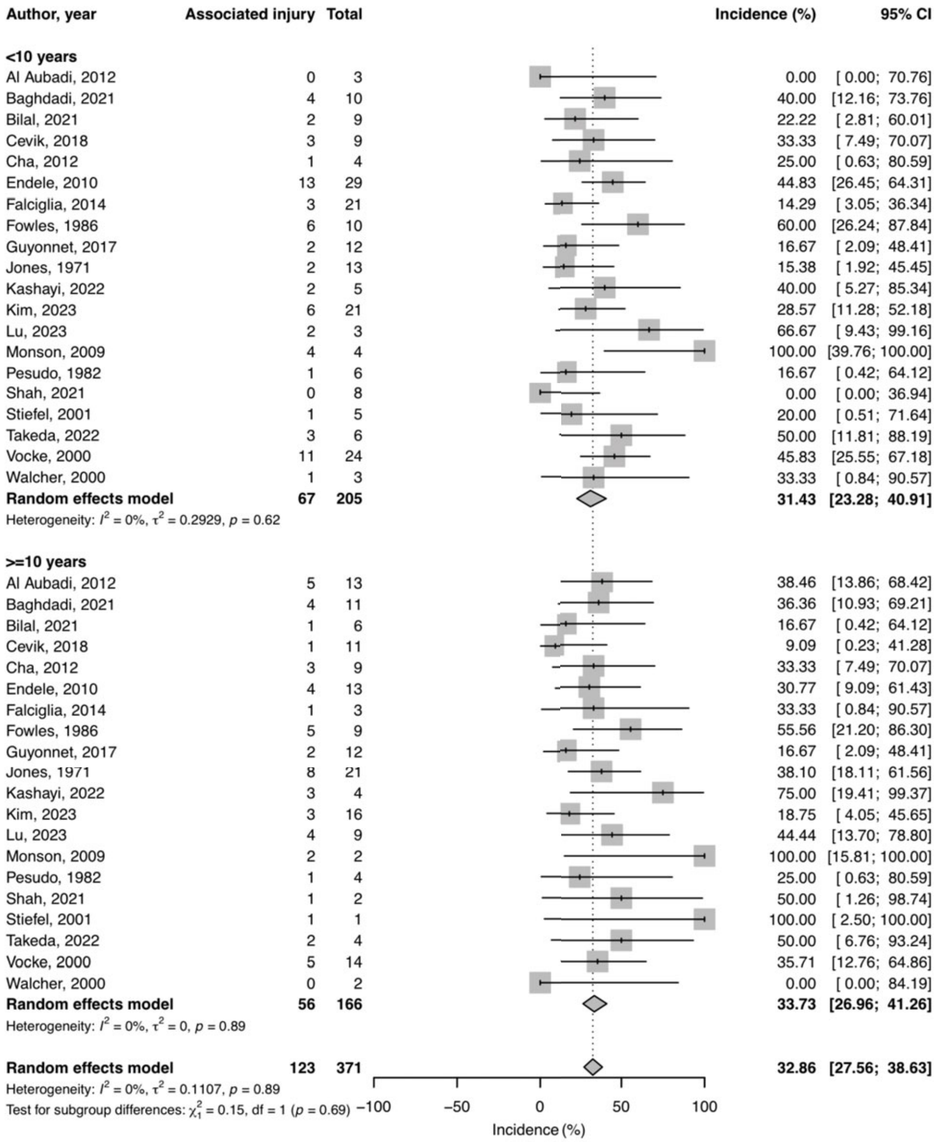
The incidence of associated injuries did not differ significantly between children under ten years compared to that in children older than ten years (Figure 3A and 4A). The percentage of associated injuries was also not correlated with Judet grade (Figure 3B and 4B).



(**A**)

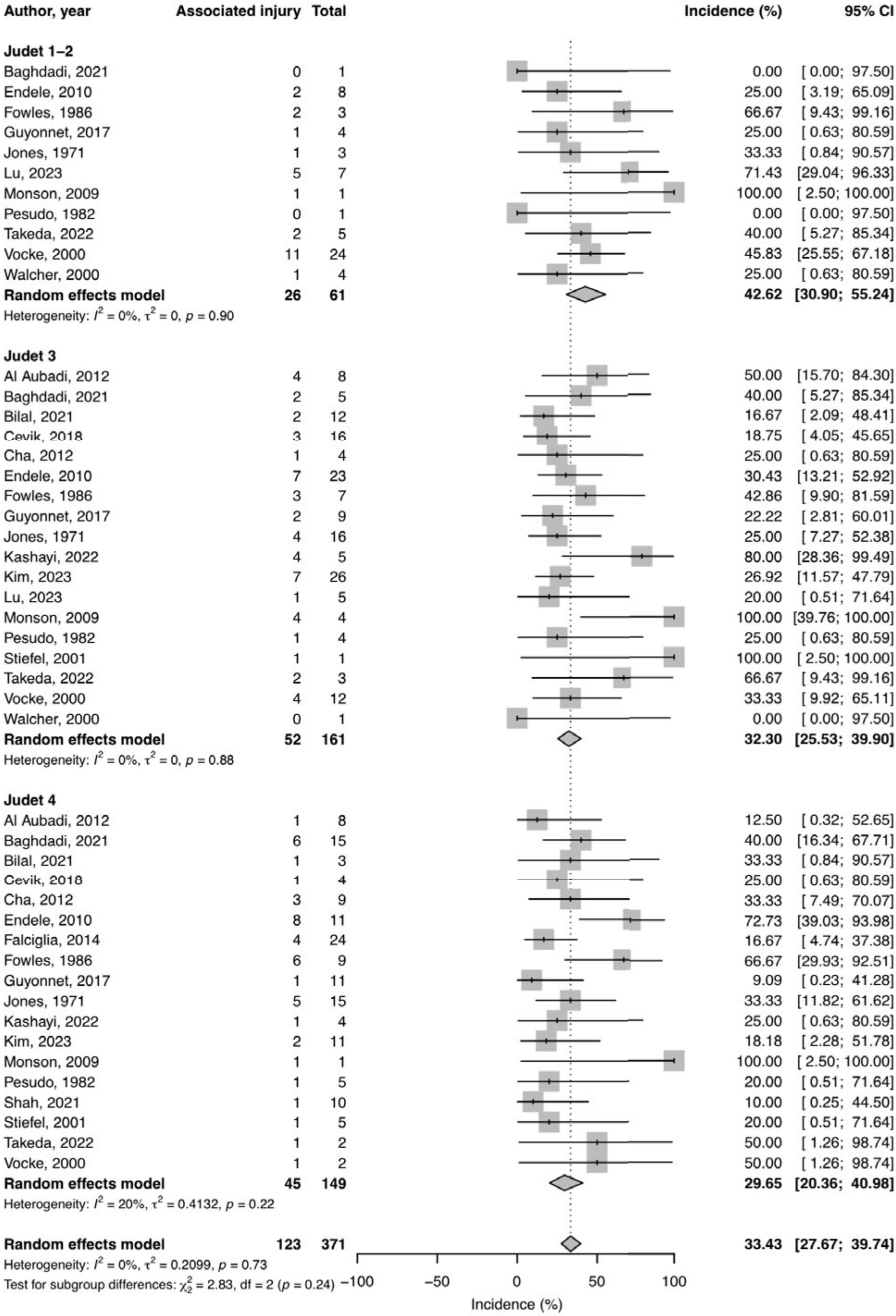
(**B**)

Figure 3. Distribution of cases among age categories and Judet grades (J). (**A**) A total of 67/205 patients under ten years of age had associated injuries, compared to 56/166 in patients over ten years of age (p = 0.694; forest plot is depicted in Figure 4A). (**B**) There is no significant difference between Judet grades for the incidence of associated injuries; p = 0.243; forest plot: Figure 4B.



(**A**)

Figure 4. (**A**) Forest plot of meta-analysis of pooled individual patient data for patient age. There is no significant difference in the occurrence of associated injuries in patient age groups of under ten years or over ten years of age (p = 0.694).



(**B**)

Figure 4 (**B**) Forest plot of meta-analysis of pooled individual patient data for fracture angulation. The Judet grade is not a predictor of the occurrence of associated injuries; CHI square $p = 0.243$[10, 22, 26-43].

Discussion

This is the first study that has used pooled individual patient data (IPD) to perform an epidemiological overview of the types of associated injuries in pediatric radial neck fractures (pRNFs) and their incidence while correlating their presence with Judet grade or age. The meta-analysis of the IPD from 371 children with a pRNF showed that around one-third of these children had associated injuries, regardless of their Judet grade or age. Despite the fact that it has been speculated in the literature that a higher fracture angulation represents a more complex injury [4, 22-24], there was no significant difference in the incidence of associated injuries between Judet 1/2, Judet 3 and Judet 4 pRNFs.

The incidence of associated injuries of 33% in our pooled data analysis complies with a previous review that analyzed the treatment outcomes in six case series of pRNFs [4] and found associated injuries in 36%.

The most commonly associated injuries are olecranon fractures, both in children under and over ten years. Dislocations are more frequently seen in older children; in our database, the first elbow dislocation was diagnosed in a seven-year-old child. In the previous literature, olecranon fractures and elbow dislocations have also been the most frequently reported associated injuries [23, 42, 71-76]. Less frequently, an associated proximal ulnar fracture, an ulnar shaft fracture or fractures of the lateral condyle of the humerus have been described [52, 71].

Fracture Classification and Trauma Mechanism

The fact that the data analysis in this study shows that the Judet classification has a similar amount of associated injuries among each grade may be an argument for revising this classification system. The most widely used classifications for assessing fracture grade are Judet [1], O'Brien [18] and the AO Pediatric Comprehensive Classification of Long-Bone Fractures (AO-PCCF [77]). All are based on radiologic criteria obtained from plain X-rays (Figure 5). The Mason classification, meanwhile, is mainly a classification system for intraarticular fractures which include the radial head, but it may also be used to grade radial neck fractures. It lacks a specific range of angulation to distinguish between fracture grades: it simply defines "slightly angulated fractures" as grade two and severely angulated fractures as grade three [21, 78]. There are multiple overlaps between these classification systems, which complicates an evaluation between the fracture grades of several classifications. For example, a grade 1 fracture according to the O'Brian classification may be a Judet grade 2 (Figure 5).

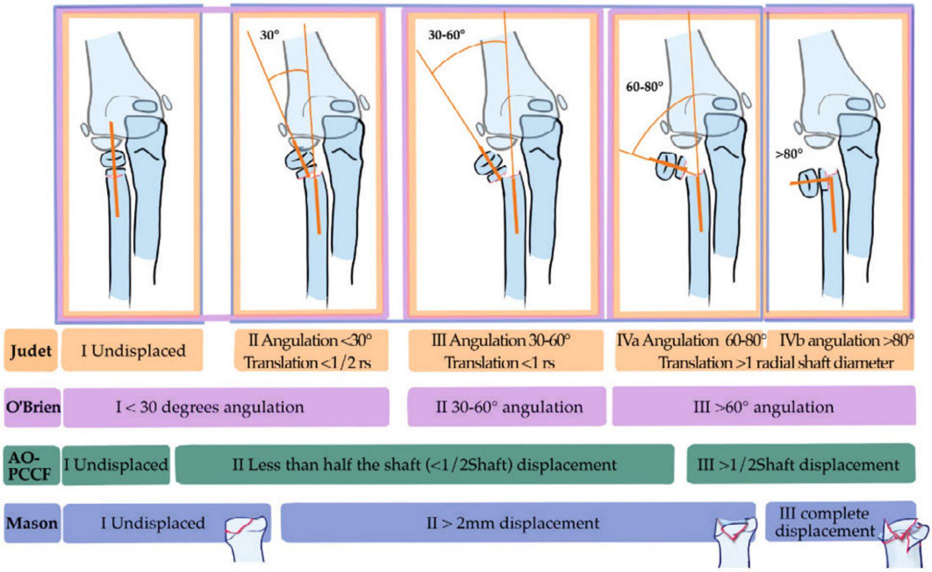


Figure 5. Overview of the most frequently used fracture classifications for pRNFs. Note that in the Mason classification, there is an overlap with intraarticular fractures of the radial head in the same classification. A Mason grade two fracture may be an intraarticular fracture with a >2 mm displacement or an extraarticular radial neck fracture with angulation. No angulation range for distinction between the three Mason grades has been specified. Following the AO-PCCF, a pRNF is coded as 21r: 2 (forearm), 1 (proximal) or r (Radius) and, depending on its location in the proximal radius, as E (epiphysis), M (metaphysis) or D (diaphysis). A separate code is added to specify the fracture pattern and the severity: I: undisplaced; II: a displacement of less than half the shaft diameter; III: a displacement of more than half the shaft diameter. rs = radial shaft. mm = millimeters.

An important conclusion is that the current classifications fail to give insights into ligamentous injuries, which may lead to underestimation of the injury severity [8, 11, 79]. An example may be a pRNF following a reduced elbow dislocation: the X-rays will show a reduced joint without additional fractures. Many authors emphasize the importance of soft tissue to the functional outcome following a radial neck fracture [3, 4, 43]. For instance, interposition of the annular ligament has been described, which is not visible in radiographs [32]. An avulsion of the medial collateral ligament may become trapped in the ulnohumeral joint [8]. Using a classification system that does not address soft tissue injuries might result in missing these injuries at initial presentation [8]. The fact that the ossification centers around the elbow become visible in plain X-rays at varying ages may thereby further complicate an adequate diagnosis.

A classification system based on the trauma biomechanics may be more reliable in predicting which structures are potentially injured [80-82] and may aid in the detection of occult fractures [8]. In adults, deduction of the trauma mechanism and injury biomechanics has also been promoted to guide clinicians in optimizing the treatment [83, 84]. In line with this, proposals have been made to also address ligamentous injuries in the Mason classification for radial head fractures [85, 86].

Two classifications used less often include a deduction of the trauma mechanism. The Chambers classification distinguishes between a radial head displacement (a valgus injury or dislocation injuries) and a primary radial neck displacement. Still, it does not address the potential risk of associated injuries (Figure 6 [19, 82, 87]).

Jeffery's classification notes the importance of medial collateral ligament injuries. An evaluation of two trauma mechanisms was published in 1972 [88], which identified compression and valgus load as the leading cause of pRNFs. Associated injuries in this classification included avulsion of the medial ligament (type 1A), which may include the medial epicondyle (type 1B) or an olecranon fracture (type 1C, Figure 6).

Both the Chambers and Jeffery's classifications include a fracture type that occurs in elbow dislocation. A posterior shift or (sub)luxation of the elbow joint may cause the capitellum to catch the radial head and lead to a completely tilted radial neck [88]. An image of a laterally tilted radial head that is taken in full supination may mimic this fracture type. In these cases, there is a risk of aberrant fixation of the radial head in a reversed position, which is an essential pitfall of treatment [84].

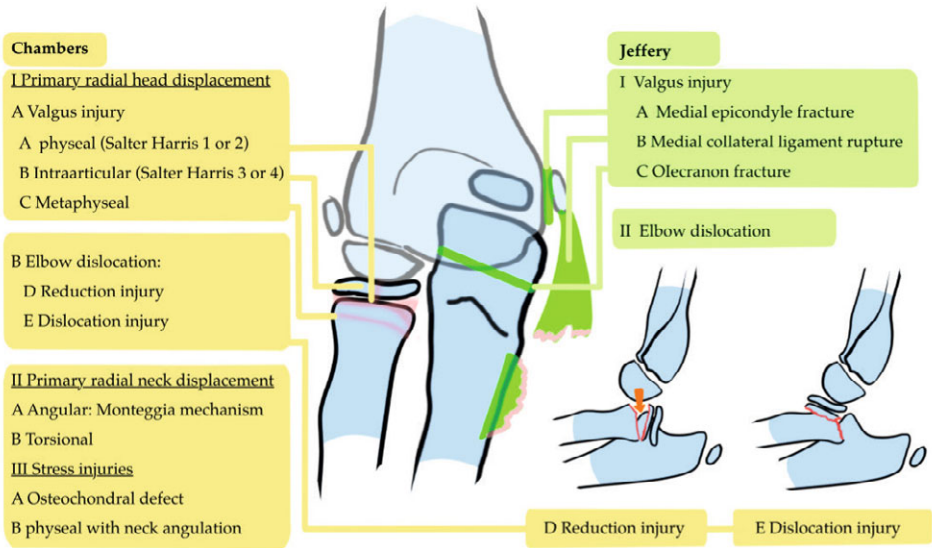


Figure 6. The Chambers classification and Jeffery classification. In these classifications, a valgus trauma mechanism is recognized with several associated injuries depending on the trauma mechanism.

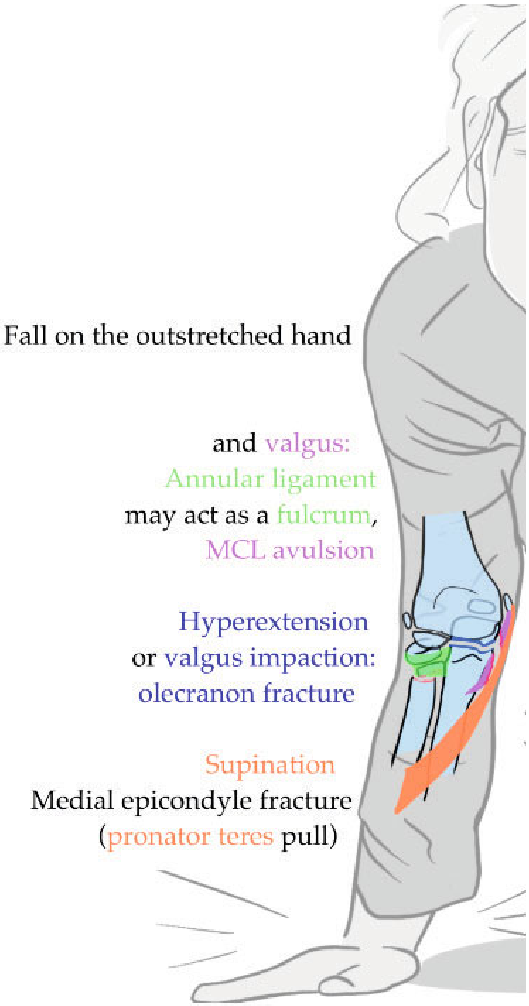


Figure 7. Most frequently described trauma mechanisms for pediatric radial neck fractures and explanation of potential biomechanic pathways of associated injuries. Note that the intact annular ligament may act as a fulcrum. An olecranon fracture may occur due to valgus compression or impingement on the olecranon fossa or as an avulsion of the triceps. Purple: medial collateral ligament (MCL); overlying orange muscle in valgus supination: pronator teres muscle; green shade overlying radial head: annular ligament.

It is generally agreed that pRNFs mainly occur due to valgus force [4, 11, 81, 89], and the intact annular ligament may function as a fulcrum (Figure 7 [38, 90]). It is presumed that the direction of pRNF angulation is determined by the rotation of the forearm during the fall [87]. In supination, the pull from the pronator teres muscles and flexor muscles may increase and hence cause avulsions or injury to the medial epicondyle [23, 38, 91].

Three additional "patterns of injury" have also been described, which include an anterior (sub)luxation of the elbow, a lateral shift of the lower arm or injuries including anterior radial head dislocation (Monteggia-like injuries [81]). The latter may be related to varus motion during trauma [8, 79], whereas radial head fractures are mostly impaction injuries in hyperextension, often with concomitant fractures of the coronoid [85, 86, 92, 93].

Monteggia injuries and Galleazi lesions should be seen as transverse unstable forearm injuries, which also include injury to the interosseous membrane [94]. In a Monteggia injury, there is a disruption of both the proximal radioulnar joint and the radiocapitellar joint [95], which should be seen as a different injury pathway. The treatment and follow-up of these lesions differ from the treatment of radial neck fractures, whose trauma mechanism is entirely different. While treating pRNFs, knowledge of the trauma biomechanics is therefore essential.

Types of Associated Injuries

Olecranon and ulna fractures occurred most frequently in the meta-analysis of this study, followed by elbow dislocations. Chambers stated that an olecranon fracture occurs due to compression [87], whereas hyperextension may also induce these types of fractures due to impingement on the olecranon fossa [79]. Olecranon fractures have also been reported in combination with elbow dislocations [4, 96]. The fracture pattern of the olecranon may be important to the choice of treatment [95]. For example, shear fractures of the olecranon (Newman type 4 [95]) are unstable fractures that require internal fixation [81].

Soft tissue injuries are reported less frequently, potentially because these injuries are more frequently overlooked at initial presentation [8, 79]. As noted, especially in very young children, diagnosing associated injuries may be difficult because history-taking may be more challenging; young children are generally more flexible, which complicates a diagnosis of instability; and a physical examination may be difficult in a child experiencing pain.

Associated Injuries and Influence on Outcome

The influence of associated injuries on the outcome following a pRNF is still debated. Studies that have evaluated the effect of associated injuries on the outcomes following a pRNF report variable outcomes. In a series that performed a univariate analysis, no significant difference in the outcome was described in eight studies [34, 52, 97-102], while a significantly worse outcome in pRNFs with associated injuries was found in two studies [33, 100]. Others have provided descriptions of their outcomes without a statistical analysis; a poor outcome was reported in ten case series [10, 14, 17, 22, 43, 62, 103-106], and five found no influence [13, 32, 52, 99].

One explanation for why an analysis of the outcome following a pRNF is complex is that there is a large confounding influence of treatment through open reduction (OR). Concomitant injuries may cause more pRNF instability and hence higher rates of ORs [71, 107]. Thereby, the decision among surgeons to indicate an OR varies. Whereas most authors have described the presence of associated injuries as not influencing their choice of treatment [39], there have also been examples of surgeons who chose to perform an open reduction in every case with an associated injury [99, 108]. In series where ORs could not have been an influencing factor, the results regarding the outcome of associated injuries are ambiguous. One case series that solely published data from patients that had an OR found no influence of the presence of associated injuries on their postoperative outcomes [99]. On the contrary, an evaluation of children who had a closed reduction showed that associated injury was still a predictor of a less favorable outcome [104]. It is thereby generally accepted that a higher complication rate is present following open reduction [12, 15, 16, 100, 106]. There is discussion on whether the worse results following ORs are caused by a more severe initial trauma or by the harmful effects of the surgical intervention [16, 26, 101]. Open surgery may cause damage to the vascularization or impairments to ROM due to the formation of fibrous tissue [36]. In a prospective study that included cases with 20 years of follow-up, functional impairment was mainly seen after growth disturbance following OR [26]. There may be an indication for intensified follow-up of this patient group because late sequalae of OR have been reported more often [14, 24]. A multivariate analysis is needed that corrects for the influence of open surgery to clarify the influence of associated injuries on the outcomes following pRNFs.

Even though there is still discussion regarding the influence of associated injuries on the outcomes of pRNFs, the importance of diagnosing a ligamentous injury may be underestimated. Specific associated injuries may require an injury-specific treatment or follow-up. For instance, stiffness of the elbow may occur more often following an elbow dislocation [24]. It is important to realize that an elbow dislocation which involves a proximal radius fracture and a coronoid fracture (also known as the “unhappy triad”) is a rare injury in children and often results from a high-energy injury [76]. Thereby, if the medial collateral ligament is torn, the reduction in the displaced radial neck fracture may not be contained due to a lack of stability in the elbow [35, 71]. In a study that evaluated the effect of ruptures of the medial collateral ligament (MCL), all pRNFs had MCL lesions in MRI scans that were performed at the moment of presentation [75]. Again, awareness of a potential ligamentous injury through deduction of the trauma mechanism may avoid missing these injuries.

There are some limitations to this study. Bias may apply because multiple case series on pRNFs that did not publish data on associated injuries could not be included. It is uncertain whether associated injuries were not present or whether they went unnoted. As explained above, many associated injuries may not have been diagnosed initially, and the incidence numbers may have been higher if MRI were used instead of only plain radiographs. However, in young children, it may be challenging to perform an MRI scan, especially in the acute setting. Thereby, mixed terminology and classifications that include intra- and extraarticular fractures [109], like the Mason classification [110], restricted the meta-analysis of the individual patient data. Heterogenous reporting [111], which is reflected in the low MINORS scores, complicated an analysis of patient and injury data other than those presented in this article. Some case series included Monteggia lesions [112], which were registered as associated injuries. It can be disputed whether the fracture classification was correct in these cases, which may have caused bias in the incidence calculations.

As pointed out before, associated injuries in radial neck fractures are frequently missed [8, 11, 17, 75, 80]. In one case series, no associated injuries were described, while one figure showed evident ulnar bowing [67]. Another pointed out that several associated medial epicondylar fractures were first diagnosed at follow-up after initially being missed [17]. It is possible that cases published as isolated radial neck injuries had, in fact, concomitant injury to the ligaments or epiphysis of the epicondyles that went unnoted. Future research focusing on the outcomes of pRNFs should include an accurate diagnosis of soft tissue injury at presentation using MRI. Ideally, prospective inclusion of consecutive patients with a set follow-up would provide clarity on the outcome of specific ligamentous injuries associated with radial neck fractures.

Conclusions

This study is the first to provide a meta-analysis of pooled individual patient data for associated injuries in pediatric radial neck injuries and assess the correlation between the incidence of associated injuries in pRNFs and the patient’s age or fracture angulation, as embedded into the Judet classification.

The incidence of associated injuries does not differ significantly in patients under and over ten years of age. Also, a higher Judet classification was not correlated with the presence of associated injuries, contrary to the currently accepted assumption that a higher fracture angulation may be related to a more complex injury.

This meta-analysis highlights the need for clinicians to adopt a trauma mechanism-based approach rather than relying solely on radiological classifications like the Judet classification. Not only will there be a smaller chance of missing associated injuries at presentation but the maltreatment of pRNFs associated with elbow dislocation may also be prevented. Future research should focus on integrating ligamentous and soft tissue injuries into comprehensive fracture classifications.

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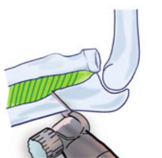

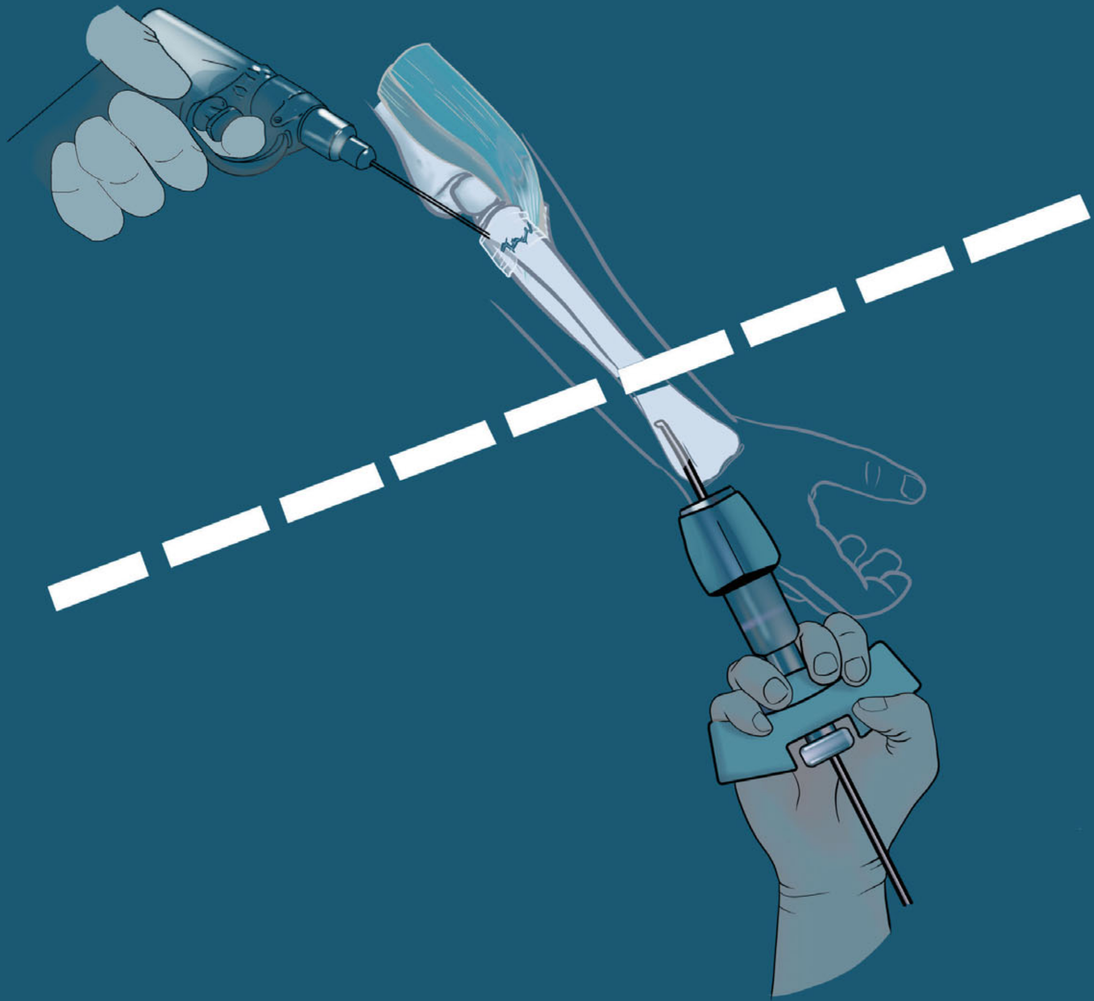

CHAPTER 05

Pediatric Radial Neck Fractures:
A Systematic Review Regarding the Influence of Fracture Treatment on Elbow Function

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Published, Children (Basel), 2022 Jul 14;9(7):1049.
doi: 10.3390/children9071049.

Abstract

Background This review aims to identify what angulation may be accepted for the conservative treatment of pediatric radial neck fractures and how the range of motion (ROM) at follow-up is influenced by the type of fracture treatment.

Patients and Methods A PRISMA-guided systematic search was performed for studies that reported on fracture angulation, treatment details, and ROM on a minimum of five children with radial neck fractures that were followed for at least one year. Data on fracture classification, treatment, and ROM were analyzed.

Results In total, 52 studies (2420 children) were included. Sufficient patient data could be extracted from 26 publications (551 children), of which 352 children had at least one year of follow-up. ROM following the closed reduction (CR) of fractures with <30 degrees angulation was impaired in only one case. In fractures angulated over 60 degrees, K-wire fixation (Kw) resulted in a significantly better ROM than intramedullary fixation (CIMP; Kw 9.7% impaired vs. CIMP 32.6% impaired, $p = 0.01$). In more than 50% of cases that required open reduction (OR), a loss of motion occurred.

Conclusions CR is effective in fractures angulated up to 30 degrees. There may be an advantage of Kw compared to CIMP fixation in fractures angulated over 60 degrees. OR should only be attempted if CR and CRIF have failed.

Keywords: elbow motion; pediatric radial neck fracture; radial neck angulation.

Introduction

Although radial neck fractures in children occur frequently, there is no consensus on the optimal treatment. The indication to perform a (surgical) reduction varies widely; some authors advise striving for anatomical reduction of the radial neck, and others accept up to 60 of fracture angulation[1-7]. Several treatment options are available. Closed reduction (CR) without fixation, closed reduction with intramedullary pinning (CIMP) with or without pin rotation, K-wire lever age and K-wire pinning (Kw), and open reduction or combinations of the aforementioned options may be used.

There is no consensus yet on the fracture angulation threshold for surgical intervention and which surgical technique should be used. Loss of motion is reported to be the most important cause of a poor outcome[8]. Therefore, the purpose of this systematic review was to compare the elbow function following different types of treatment in relation to the angulation of the pediatric radial neck fracture. With this research, we aimed to find out which treatment modality for different types of pediatric radial neck fractures results in the best elbow function.

Patients and Methods

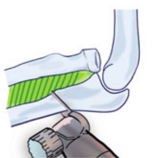
This study followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The protocol for this systematic review is registered in the PROSPERO database http://www.crd.york.ac.uk/PROSPERO/ (accessed on 7 May 2022), (registration number CRD42018088696).

Search Strategy

A health science librarian of our institution, with extensive experience in the conduct A health science librarian of our institution, with extensive experience in the conduct of literature searching for systematic reviews, assisted in designing and performing the search[9]. The following databases were searched: Embase, Cochrane Central Register, Medline, Web of Science, PubMed Publisher, and Google Scholar. The following main keywords were used: radial neck fracture, angulation, elbow, outcome, pronation, and supination. The search strategy for each database is outlined in Appendix A of this paper. The databases were searched from inception to 17 November 2021 (Figure 1).

Study Selection

The results from all databases were combined, and duplicate titles were removed. Two authors (K.I.M.v.d.E. and G.J.B.) screened all titles, abstracts, and full articles independently. The results from all databases were combined, and duplicate titles



were removed. Two authors (K.I.M.v.d.E. and G.J.B.) screened all titles, abstracts, and full articles independently. The inclusion and exclusion criteria are listed in Table 1. Disagreements were solved by discussion, and a final decision was made by a third reviewer (J.W.C.) if there was disagreement. Patients with less than one year follow-up were excluded.

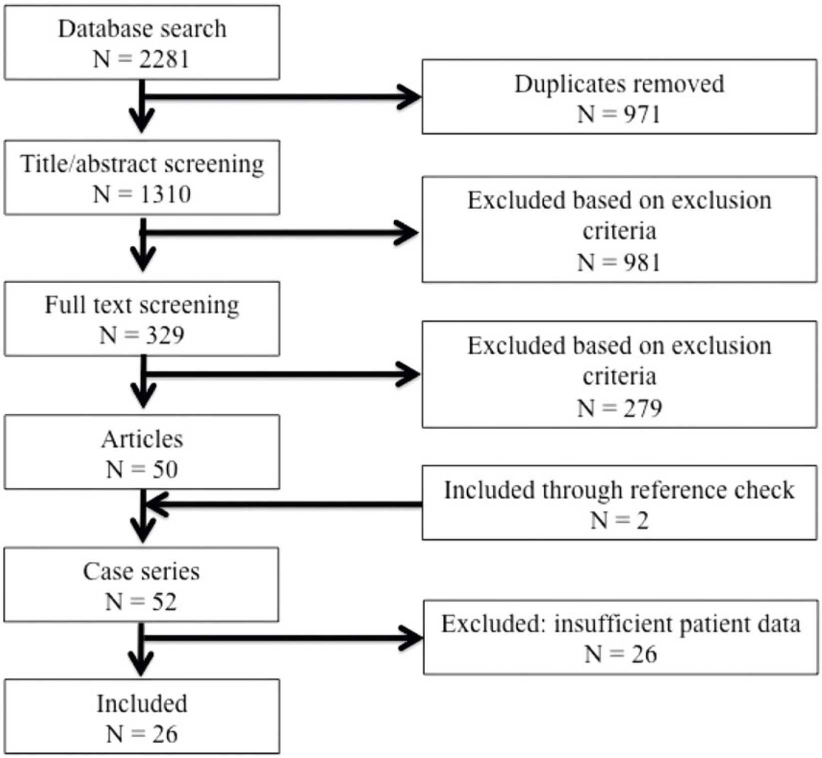


Figure 1. PRISMA-guided search.

Inclusion Criteria	Exclusion Criteria
Prospective or retrospective follow-up study	Review/meta-analysis
≥5 children with radial neck fractures	Age > 16 years
Fracture angulation should be reported	Elbow prosthesis
Radiological imaging at presentation	Animals
Outcome: range of motion at follow-up	Less than one year follow-up
Outcome linked to fracture angulation and treatment	
Language: English, Dutch	

Table 1. Inclusion and exclusion criteria

Risk of Bias Assessment

The risk of bias was assessed by using the prognostic checklist adapted from the Cochrane handbook for systematic reviews, chapter 7[10] (see Table 2). Each study was scored for selection bias, information bias, and confounding. Two authors (K.I.M.v.d.E. and G.J.B.) assessed the quality of the included studies independently. If consensus was not reached after discussion, a third reviewer (M.R.) was consulted. Finally, article quality was screened using the MINORS criteria; an overview is listed in Table 3.

Table 2. Risk of bias assessment based on the adapted Cochrane

Author	Selectionbias	Informationbias	Confounding
Al-Aubaidi (2012) [11]	green	orange	red
Bilal (2021) [12]	orange	green	green
Brandão (2010) [13]	green	green	orange
Çevik (2018) [14]	green	green	green
Cha (2012) [15]	green	green	green
Cossio (2014) [16]	green	green	green
Endele (2010) [17]	green	orange	orange
Falciglia (2014) [8]	orange	orange	green
Fowles (1986) [18]	red	red	red
Futami (1995) [19]	red	green	green
Gutierrez-de la Iglesia (2015) [20]	orange	green	orange
Jones (1971) [21]	orange	orange	orange
Klitscher (2009) [22]	orange	orange	green
Koca (2017) [23]	green	orange	orange
Massetti (2020) [24]	green	green	green
Metaizeau (1993) [25]	orange	orange	orange
Monson (2009) [26]	green	red	red
Shah (2020) [27]	green	orange	orange
Stiefel (2001) [28]	green	green	red
Tanagho (2015) [29]	orange	red	orange
Tarallo (2013) [30]	green	orange	green
Tibone (1981) [31]	green	orange	orange
Ugutmen (2010) [32]	green	orange	orange
Walcher (2000) [33]	green	green	orange
Yallapragada (2020) [34]	green	orange	orange
Zhang (2016) [35]	orange	green	red

Scores: green = low risk, orange = moderate risk, red = high risk.

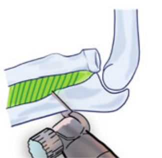


Table 3. Part a: Overview of included articles

(a)

Author	Year	Fracture Classification	Injury Type	N	1y FU	Mean Age in Years (Range)	Mean Follow-Up in Years (Range)	Outcome
Al-Aubaidi [11]	2012	Steele	all pt w/open physis treated with metaizeau	16	16	12 (9–15)	3.3 (1.3–6.3)	DASH
Bilal [12]	2021	>30°	>30°,intramedullary nailing (TEN)	15	15	10.1 (6.4–15.8)	2.1 (1.3–3)	Tan&Mahadev
Brandão [13]	2010	O'Brien	O'Brien type 3	28	26	8.6 (6–13)	4.3 (1.7–10)	radiologic union, ROM
Çevik [14]	2018	Judet	Judet 3/4	20	20	9.75 (4–13)	2.9 (1.1–7)	ROM
Cha [15]	2012	Judet	Judet 3/4	13	13	10.4 (6–13)	3.5 (2.4–4.4)	flynn score
Cossio [16]	2014	Judet	Judet 3/4	9	9	9.1 (6–12)	2.2 (1–3)	Tibone
Endele [17]	2010	Judet	all RN# in a retrospective period	54	42	8 (1-13)	4 (0.5–11)	ROM
Falciglia [8]	2014	O'Brien	all RN# in a retrospective period without success of CR or KW	24	24	7.1 (4.3–10.2)	7.1 (3.2–12.1)	MEPS
Fowles [18]	1986	<20°, >20°	all RN# in a retrospective period	23	17	9.1 (5–13)	1.5 (0.7–2.8)	ROM
Futami [19]	1995	none	angulated RN# (not specified)	10	10	9 (6–13)	u	Tibone and Stolz
Gutierrez-de la Iglesia [20]	2015	Judet	Judet 3/4	51	0	8 (3–15)	1.2 (0.7–3.3)	Tibone and Stolz, Ursei
Jones [21]	1971	15–29°, 30–59°, 60–90°	all RN# in a retrospective period	34	18	10 (5–13)	5 (1–14)	Steele
Klitscher [22]	2009	Judet	Judet 3/4	28	0	8 (5–11)	2.7 (0.5–5.6)	MEPS, Metaizeau
Koca [23]	2017	Judet	Judet 3	11	11	7.7 (6–10)	2.0 (1.7–2.7)	Leung/Peterson
Massetti [24]	2020	judet	Judet 3/4	20	0	7.8 (2–11)	0.7–3.8	MEPS
Metaizeau [25]	1993	Judet	Judet 3/4	47	47	10.7 (5–13)	4 (ns)	MEPS
Monson [26]	2009	Degrees	all RN# in a retrospecitve period	6	6	9.5 (6–11)	0.36	Morrey, Metaizeau
Shah [27]	2020	Judet	Judet 4	10	10	8.6 (6–12)	1 (0.8–1.3)	Steinberg, Rodriguez-Merchan
Stiefel [28]	2001	Judet	Judet 4	6	6	8.4 (7–10.8)	u (0.75–2.5)	ROM
Tanagho [29]	2015	Steele	isolated metaphyseal RN# >30°	9	9	9.6 (u)	1.6 (u)	Own rating system
Tarallo [30]	2013	Judet	Judet 3/4	20	20	11 (6–16)	3.5 (1.3–5.3)	MEPS, Metaizeau
Tibone [31]	1981	Degrees	all RN# in a retrospective period	23	23	9.2 (4–14)	3.15 (2.0–8.0)	ROM
Ugutmen [32]	2010	Judet	RN# with open growth plates	16	16	8 (6–13)	2 (1.5–3.3)	Metaizeau
Walcher [33]	2000	Judet	Judet 2/3, failed CR	5	0	7 (u)	3 (u)	ROM, own rating system
Yallapragada [34]	2020	Judet	Judet 3/4	21	0	8 (u)	0.4 (0.3–0.5)	OES, Metaizeau
Zhang [35]	2016	Judet	Judet 3/4	50	0	8.4 (5.6–13)	2 (u)	MEPS
				569	352	8.96	2.69	
				(b)				

Table 3. Part b: MINORS criteria

Author	Year	MINORS Total	Aim	Consecutive Cases	End Points	Bias	Follow-Up	Lost to FU	Study Size
Al-Aubaidi [11]	2012	7	1	2	1	0	2	1	0
Bilal [12]	2021	6	1	1	2	1	2	0	0
Brandão [13]	2010	10	2	2	2	1	2	1	0
Çevik [14]	2018	10	2	2	2	2	2	0	0
Cha [15]	2012	10	2	2	2	2	2	0	0
Cossio [16]	2014	8	1	1	2	2	2	0	0
Endele [17]	2010	9	1	1	2	1	2	2	0
Falciglia [8]	2014	8	2	1	2	1	1	1	0
Fowles [18]	1986	8	1	2	1	0	2	2	0
Futami [19]	1995	2	0	0	0	0	2	0	0
Gutierrez-de la Iglesia [20]	2015	8	2	1	2	1	2	0	0
Jones [21]	1971	8	1	1	1	1	2	2	0
Klitscher [22]	2009	9	1	2	2	1	2	1	0
Koca [23]	2017	8	2	1	2	1	2	0	0
Massetti [24]	2020	5	2	1	1	2	1	0	0
Metaizeau [25]	1993	7	2	1	2	1	1	0	0
Monson [26]	2009	3	1	1	1	0	0	0	0
Shah [27]	2020	4	0	2	1	1	1	0	0
Stiefel [28]	2001	4	2	1	1	0	0	0	0
Tanagho [29]	2015	4	1	1	0	0	1	1	0
Tarallo [30]	2013	8	2	1	2	1	2	0	0
Tibone [31]	1981	9	1	2	2	1	2	1	0
Ugutmen [32]	2010	5	1	1	1	1	1	0	0
Walcher [33]	2000	4	1	1	0	1	1	0	0
Yallapragada [34]	2020	4	1	1	1	1	1	0	0
Zhang [35]	2016	6	2	1	1	0	2	0	0

u = unknown; RN# = radial neck fractures; ROM = range of motion; MEPS = Mayo Elbow Performance Score; OES = Oxford Elbow Score.

Data regarding study design, number of children, age, fracture classification, type of surgical intervention or conservative therapy, range of motion (ROM) at presentation, ROM at follow-up, and complications were extracted by one reviewer (K.I.M.v.d.E.). Characteris tics are listed in Table 3. The primary outcome was ROM of the elbow at follow-up.

Data Analysis

Each study was analyzed for individual patient data on preoperative angulation, method of treatment, and postoperative range of motion. Data regarding radial neck angulation (30, 31–60, and >60) and treatment were extracted from articles or obtained from authors. If published articles provided insufficient patient data to be included for the data analysis, the authors were contacted with a request for individual data if contact details were available. For each received treatment, the ROM at follow-up was evaluated (Table4). Four different treatment groups were identified: no reduction or closed reduction only (CR); closed reduction followed by internal fixation (CRIF), either with K-wire fixation (Kw) or closed intramedullary pin fixation (CIMP); or open reduction (OR). If there was no full range of motion at follow-up (defined as at least 5 degrees of impairment in any direction described by the authors), the outcome was scored "impaired".

Differences in outcomes for several groups were statistically analyzed by the Chi-Square Fisher Exact test ($p<0.05$), using the software SPSS Statistics for Windows, Version 27.0 (IBM Corp. Released 2020, IBM, Armonk, NY, USA).

Results

Of the 2281 publications found by our search, 52 series of pediatric radial neck fractures were of potential interest. Other than Cevik et al.[14], Cha et al.[15], and Cossio et al.[16], all studies showed some risk of bias. Selection bias was seen in 10 papers, information bias in 15 papers, and confounding in 18 papers (see Tables 2 and 3).

Twenty-six case series provided sufficient data regarding angulation at trauma, treatment details, and elbow ROM at follow-up[36–60]. The main characteristics of the included studies are listed in Table 3. All studies had a retrospective design. In total, 551 pediatric cases could be included, ranging from 5 to 54 children per study[8,11,13–18,20–23,25,26,28–33,35].

All fractures were divided into three groups based on the degrees of fracture angulation following the classifications of O'Brien and Judet[5,7]: <30° (35 cases), 31–60° (247 cases), and >60° (269 cases). In total, 352 of these patients had a follow-up of at least one year. Results are depicted in Table 4, which includes data from nineteen articles[8,11,13–16,21,23,25,30–32].

Table 4. Data analysis of 352 pediatric patients who sustained a radial neck fracture and had at least 1 year follow-up.

Fracture Angle	N (%)	Treatment Groups	N with Loss of Motion (% of Treatment)	N (% of Angulation Group
≤30°	25 (7.1)	CR	1 (7.7)	13 (52.0)
		CRIF	0	11 (44.0)
		CIMP	0	11 (44.0)
		Kw	0	0
		OR	1 (100)	1 (4.0)
		Group sum	*2 (8.0)*	
31–60°	152 (43.2)	CR	7 (63.6)	11 (7.2)
		CRIF	12 (9.4)	127 (83.6)
		CIMP	10 (9.5) NS$	105 (69.1)
		Kw	2 (9.1) NS$	22 (14.5)
		OR	7 (50)	14 (9.2)
		Group sum	*26 (17.1)*	
>60°	175 (49.7)	CR	0	0
		CRIF	33 (26.4)	123 (70.3)
		CIMP	30 (32.6) *@	92 (52.6)
		Kw	3 (9.7) *@	31 (17.7)
		OR	31 (59.6)	52 (29.7)
		Group sum	*64 (36.6)*	
>30° (31–60° and >60° combined)	327 (92.9)	CR	7 (63.6) *^	11 (3.4)
		CRIF	45 (18.0) *^	250 (76.5)
		CIMP	40 (20.3) NS#	197 (60.2)
		Kw	5 (9.4) NS#	53 (16.2)
		OR	38 (55.1)	66 (20.2)
		Group sum	*90 (27.5)*	

CR = closed reduction without fixation or immobilization only; CRIF = closed reduction internal fixation;
OR = open reduction; CIMP = retrograde intramedullar fixation; Kw = percutaneous fixation with K-wire.
N = number of patients; *: significant difference; NS: non-significant difference. $: In the group angulated
31–60, there is no significant difference between Kw and CIMP, $p = 0.950$. ^: In the >30 angulated patients, there
is a significant difference between CR (without fixation) and CRIF (CIMP and Kw) fixation; $p < 0.001$. #: In the
>30 angulated patients, there is no significant difference between IM fixation or Kw fixation, $p = 0.007$. @: In the
>60 angulated patients, there is a significant difference between Kw and CIMP; $p = 0.001$.

Treatment options consisted of cast immobilization without reduction; closed reduction[26,27], which may be aided by leverage of a percutaneous pin[61]; K-wire fixation (either transcapitellar[18,62], across the fracture[41], by percutaneous K-wire leverage and pinning[15,16,19,29,33,46,49,52]); intramedullary K-wire[24,32]; Nancy nail or Titanium elastic nail (TEN)[1] [1,13,22,23,25,28,34,36,54,55] combined techniques such as CIMP assisted by Kw leverage[14,17,30,43,50,53,57]; open reduction only[8]; or the description of several treatments[20,21,31,35,37–39,42,45,47,56,59,60]. Some included (slight) adjustments to established techniques[12,58].

Children with a fracture angulation of <30° who were treated with CR showed loss of motion in 7.7% at follow-up. In fractures angulated over 30 degrees, 63.6% of conservatively treated children had impaired ROM (7/11 cases). The outcome following CR was significantly worse compared to patients treated with CRIF (either Kw fixation or CIMP), in angulation >30 degrees (CR 7/11 (63.6%) impaired vs. CRIF 45/250 (18.0%) p-value < 0.001).

A closed reduction with intramedullary pinning was most frequently performed (250 patients in total) in both the 31–60° and >60° group. If only the groups over 30 degrees angulation are compared, there was a significantly better outcome following K-wire fixation than following CIMP (Kw vs. CIMP 5/53 (9%) vs. 40/197 (20%); p-value < 0.001). This is also true for a separate analysis of the >60° group (K-wire vs. CIMP 3/31 (9.7%) vs. 30/92 (32.6%) impaired, p-value of 0.001), but a separate analysis of Kw vs. CIMP in the 31–60° group yields a non-significant difference (Table 4). Overall, there was no significant difference between Kw and CIMP.

Open reduction resulted in an impaired range of motion in about 60% of cases. All but one OR had been performed in fractures angulated over 30°. Nine separate articles published data on open reductions (OR), but the numbers were too small for a statistical analysis. Following OR, there had been 7 fractures without fixation, 11 with IM fixation, and 18 with K-wire fixation; 3 were not described in detail.

Discussion

To our knowledge, this is the first systematic review that performed a pooled analysis that focused on range of motion as an outcome following pediatric radial neck fracture treatment.

Overall pediatric radial neck fractures resulted in impaired elbow function in 26% of cases. Radial neck fractures with an angulation of <30° demonstrated good results with CR. Fractures angulated >60° showed the least ROM impairment if K-wires were used. Open reduction had been mostly used in severely angulated fractures and often ended in an impaired elbow function.

In the literature, there is a wide variety of different scales and ratings to report radial neck fracture outcomes[63]. Only a few authors used a validated outcome scale, such as the Mayo Elbow Performance Scale (MEPS) or the (quick)DASH (Table 3). Many used their own rating system to judge the clinical or radiological outcome, which led to low comparability. Thereby, most authors only published the mean outcomes of certain groups of patients or mixed outcomes of several fracture classifications. Data pooling of individual patient cases and a meta-analysis for various treatments and their outcomes were hence impossible; the only analysis that could be performed on the extracted data was an evaluation of the outcome of range of motion based on fracture classification.

CR and Indication for Fracture Reduction

All children who were treated with immobilization or closed reduction only received a long arm cast (or collar and cuff sling under the clothes[21]). In the studies of Fowles and Kassab[18]

1 2 3 4 5 6 7 8 9 10 AI AII AIII AIV AV AVI AVII AVIII

and Jones and Esah[21], the elbows were immobilized for 3 weeks. For all other conservative treatments, the duration of immobilization was unclear[20,26,31]. Overall, no manipulation was performed when the initial angle was <30°, and closed reduction was indicated when the initial angle was >30°. An exception is an article by Jones[21] that advised fracture reduction when angulation exceeded 15 degrees. Closed reduction was always unsuccessful in radial neck fractures angulated over 60°, following a study that evaluated the success rate of closed radial neck fracture reduction in the emergency ward[64]. The same article stated that delayed reduction that was attempted over 24 h following trauma, may be prone to failure.

Closed reduction of a radial neck fracture may be challenging and might result in residual angulation or re-displacement. In a series of 48 fractures that were reduced by closed manipulation without fixation, as many as 36 fractures remained slightly or severely unreduced[45]. The quality of the cast may play a role, which may be calculated using the casting index (CI)[65,66].

Closed reduction without osteosynthesis in fractures angulated >30 degrees showed loss of motion at follow-up in over 60% of cases (N = 11). A recent review therefore advised to consider the percutaneous fixation of a successful closed reduction [63]. Malunion was the main reason for loss of motion in this group[42,43,51]. Some stated that closed manipulation may be attempted in fractures angulated as much as 45 degrees, but if residual angulation exceeds 20 degrees, intramedullary pin fixation should be considered [25]. Others concluded that closed reduction should be considered unsuccessful if residual angulation is over 15 degrees[21].

Closed reduction may be aided by percutaneous K-wire manipulation[28,29,52,67]. Some authors, however, stated that the manipulation by the K-wire in proximity to the physis may cause abnormalities to the physis or risk of neurological damage, and advised against it[32]. Small series were published which demonstrated other options to facilitate reduction: a forceps may be introduced ulnar to the radial neck[58], or a small elevator may be introduced at the fracture site[19]. Nevertheless, in the series that described an elevator-assisted reduction technique, a premature physis fusion occurred in 4/10 patients.

Choice of Treatment and Relation to Postoperative ROM

Although one of the case series showed favorable results of CIMP [30], our combined analysis shows that there is a better ROM following K-wire fixation compared to CIMP fixation, which is significant in fractures angulated >60 degrees. Potentially, this difference may be explained by the low number of patients reported in single case series, which renders a high risk of bias.

Open Reduction (OR)

OR should only be performed when closed reduction fails. For example, the introduction of an intramedullary device may be challenging if angulation exceeds 80°[68]. A small incision (<3 cm) is recommended[20], the annular ligament should be preserved, and instruments that could damage the radial head during reduction should be avoided. The use of a "Joy stick" K-wire in the proximal fragment to aid fracture reduction is favored over the use of clamps to prevent potential damage to the posterior interosseous nerve (PIN)[69].

Poor results following OR may be caused by damage of the blood supply[70], proximal radioulnar joint adhesion[8], or periarticular ossification [57,71]. Potentially, the focal damage to tissues due to trauma plays a role[8]. Nevertheless, interposing soft tissue makes open reduction necessary in some cases[32].

In all fracture angulation groups, loss of motion was seen in about half of the children treated with open reduction. We therefore agree with Klitscher et al.[22], who stated: "Every manipulative technique should be tried before open reduction is chosen". However, there may be bias because OR was sometimes described as the last available option when closed reduction failed.

Although some authors stated that if the radial head was stable following OR, fixation was not always necessary[8], this is disputed by our high percentage of loss of ROM in non-fixated fractures after OR. Given the fact that this percentage is significantly lower in the CRIF groups, fixation by an intramedullary nail or K-wire fixation should be considered, even after OR.

The results of this systematic review are subject to some limitations. First of all, the overall level of evidence is low. Almost all articles were level 4, and some were level 3. The overall quality of included articles is mediocre, with a risk of selection bias in 10 articles, information bias in 15 articles, and confounding bias in 18 articles. Several articles described a new or modified surgical technique without a power analysis for group size[32,33], and without a statistical analysis to compare to traditional techniques or a clear comparative design. The low incidence of displaced radial neck fractures and subsequently small cohort sizes played a role. The scores for the MINORS criteria were low for all studies, mainly due to the retrospective character of all case series that were included.

Secondly, this article only focuses on fracture angulation without considering the effect of fracture translation or rotation. In addition, associated injuries, such as ipsilateral olecranon fracture, ipsilateral fracture of the medial epicondyle, or elbow instability, were not registered; however, they can be present in 50% of children suffering a radial neck fracture[31,39]. The influence of the presence of a more extensive injury on the choice of treatment for the radial neck fracture[17] or the postoperative outcome[25,40] is still subject to discussion[18]. Some authors stated ROM would not be impaired[42]; others disagreed and showed a less favorable prognosis when associated injuries were present[17,39,42,48].

Thirdly, growth can behave like a friend or an enemy in children and might affect the outcomes. Nevertheless, a radial neck fracture is near the minimal active proximal physis, which results in less correction than in distal radius fractures. To minimize the influence of correction by growth, we only included children with a minimal follow-up of one year.

The influence of immobilization in the non-conservative groups could not be calculated. There was no evidence that postoperative immobilization had any advantages[57,72], and the worse outcome in ROM was seen when the elbow was immobilized for more than three weeks[37]. It is noteworthy that almost none of the included studies mentioned physiotherapy. Only Wang et al.[57] described "exercises under supervision (. . .) 1 day after operation", and Walcher et al.[33] mentioned physiotherapy only in one complex case.

Conclusions

This systematic review shows that conservative treatment with or without the closed reduction of pediatric radial neck fractures with primary angulation up to 30° results in good elbow function. In radial neck fractures with an angulation of >60°, closed reduction followed by K-wire fixation may have an advantage over intramedullary fracture fixation, but this difference is not significant in fractures angulated 31–60°. Open reduction should only be performed if closed reduction fails, and caution should be taken not to (further) damage the physis and radial head vascularization.

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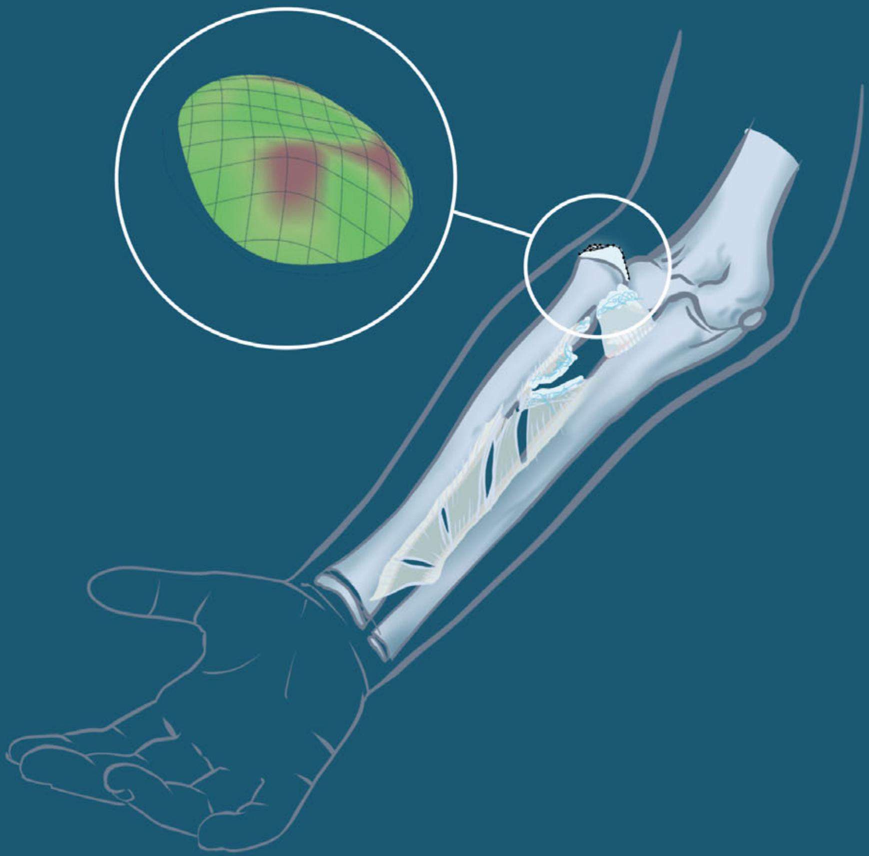
PART THREE

3

Corrective surgery for missed Monteggia injuries in children



CHAPTER 06

Radial Head Volume Measurements using Quantitative Three Dimensional CT images for Radial Head Deformation following missed Monteggia lesions

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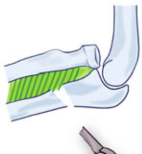
Published, JSES Int, 2022 Nov 22;7(6):2612-2616.
doi: 10.1016/j.jseint.2022.10.011



Abstract

Introduction In chronic radial head dislocation, the radial head may enlarge and become dome-shaped. To date there is no validated tool to quantify radial head deformation and predict its influence on surgical outcome. This study assesses the potential value of volume and surface calculations obtained by quantitative three dimensional CT scanning (Q3DCT) in the workup for corrective surgery in pediatric patients with missed Monteggia lesions.

Material and methods Ten consecutive pediatric patients with a missed Monteggia lesion were included (2012-2020). The volume and the articular surface size of the radial head were calculated using Q3DCT and a three dimensional reconstruction of the articular surface relief was depicted in a heat map. The head/neck ratio was calculated and compared to Q3DCT data of missed Monteggia patients and their age/sex matched controls.

Results The radial head volume and radial articular surface size did not differ significantly between patients with missed Monteggia lesions and age/sex matched controls (volume 1487 mm^3 versus 1163 mm^3, p=0,32; articular surface size 282 mm^3 versus 236 mm^3 ,p=0,33). Optically, heat maps of the articular surface of missed Monteggia patients did not differ notably from control heat maps.. A higher head/neck ratio correlated to a larger radial head volume (Pearson r=0,73; p=0,02).

Discussion and conclusion Q3DCT may be an interesting tool in the preoperative workup of pediatric missed Monteggia lesions. Prospective research with larger cohort sizes and data that compares the affected side to the contralateral elbow is needed to assess its true clinical potential.

Level of evidence: level 1

Keywords: Missed Monteggia; three dimensional CT analysis; Radial head dislocation; pediatric Monteggia; radial head dysplasia; corrective elbow surgery

Introduction

Radial head dislocations are frequently missed at presentation, especially when a Monteggia lesion is present[1,2]. Initial complaints can be mild, but increasing deformity during growth may give rise to pain[3-6], restricted range of elbow motion (ROM)[7-16], neuropathy[17,5,18], instability[16,19], a prominent radial head[16,18,20] and valgus deformity[6,16-19,21-23] of the elbow.

If a radial head dislocation exists chronically, growth disturbances may occur. In previous studies, onset of radial head deformation was noted between 3 months to 3 years following trauma[9,24-26]. Presumably the lack of pressure on the radial head causes it to become dome-shaped[3,11,26,27]. Other dysplastic features are radial head overgrowth, widening or rounding and hypertrophy of the radial head, a slender radial neck and flattening of the capitellum[2]. Many authors suggest that the success rate of corrective surgery depends on the amount of dysplastic changes of the radial head[11,13,14,19,27-29].

The recommendations for preoperative workup of chronic missed Monteggia lesions vary, some include (three dimensional (3D)) CT-scans[19,26], MRI scans[28], arthrography[17] or lateral X-rays with calculation of the head-neck ratio[7,14,27]. No threshold is known for any of the imaging techniques named above to distinguish between a “normal” or a “deformed” radial head. Most authors compare to the unaffected side, but clinical implications for the amount of radial head deformation remain vague. Currently, the head/neck ratio is often used to objectify radial head deformation. It was conceived based on the typical formation of a slender radial neck and radial head widening in posttraumatic radial head dislocation, compared to the contralateral elbow[27]. The significance of the head-neck ratio is controversial[30] and there have been no validation studies to identify a threshold that indicates a higher risk for postoperative complications. In a small cohort study from our clinic, the intraoperative aspect of the radial head, noted by the operating surgeon deviated substantially from the estimated dysplastic changes by preoperative head-neck ratio on lateral X-rays[31].

Quantitative three dimensional CT Analysis (Q3DCT) of the radial head proved to be useful in understanding intra-articular fractures[32]. It may also be a helpful non-invasive technique to measure the volume and articular surface features of the radial head[33].

This study aimed to measure and visualise the following dysplastic features: (1) radial head volume, (2) articular surface size of the radial head and (3) concavity of the radial head using Q3DCT of chronic missed Monteggia lesions. Radial head Q3DCT features were then correlated to radial head redislocation rate.

It was hypothesised that the articular surface shape would deform due to repetitive radial head dislocations.

Material and methods

All consecutive patients that reported to the Amphia hospital in Breda, the Netherlands, between January 2012 and January 2020 with a chronic radial head dislocation following a missed Monteggia lesion were approached to participate in this retrospective study. A fellowship trained musculoskeletal radiologist and the senior author identified missed Monteggia lesions. Inclusion criteria were a trauma to presentation interval of at least four weeks, age under 18 years, and workup that included a preoperative Computed Tomography (CT) scan of adequate quality. Congenital dislocations and acute presentations were excluded. Postoperative follow-up was following hospital protocol; all patients were followed up with plain radiographs of the elbow at six weeks and one year postoperatively. Several patients had longer follow-up at the surgeons' or parents' preference. Our institutional Medical Ethics Review Committee approved our research protocol and all patients agreed on anonymous use of their data for scientific purposes..

Given the retrospective study design, it was impossible to obtain a CT scan from the non-affected elbow at the moment of presentation. Therefore, each patient with a missed Monteggia lesion (cases) was 1:1 matched to a patient without a Monteggia lesion (hereafter referred to as "control patients"). Subjects were matched based on age (within 0,4 years) and sex.

Surgical procedure

All surgical procedures were performed by this study's principal investigator (DE) and included an open reduction of the radiocapitellar joint, a corrective osteotomy of the ulna, and a reconstruction of the annular ligament. Before repositioning the radial head, the surgeon judged the optical dysplastic features of the radial head (concavity, widening of the radial head) and the effort that was required for radial head repositioning. Postoperatively, a cast in 90 degrees flexion and neutral forearm rotation was applied for the duration of four weeks. After cast removal, physiotherapy was started for all patients.

Outcome measures and explanatory variables

Medical records were reviewed to extract the baseline CT scan and data at presentation, details of the performed surgery, intraoperative aspect of the radial head, and the postoperative radiograph at follow-up consultation.

The outcome measures for Q3DCT analysis were: radial head volume, radial head articular surface size, and heat map depiction of radial head articular surface concavity. CT scans were saved as Digital Imaging and Communications in Medicine files and uploaded in 3D Slicer (version 4.10.2; Boston, Massachusetts, USA). Cortical outline of the radial head was manually marked on transverse, sagittal, and coronal CT slides using a cut-off of 200 to 250 Hounsfield units in 3D Slicer. The radial head was defined as all bone proximal to the physis or physeal scar. 3D Slicer renders a 3D polygon mesh model, which was imported into Rhinoceros (Rhinoceros 5.0; McNeel, Seattle, Washington, USA). The volume of the radial tuberosity was measured in mm^3 (mm = millimeter) and the articular surface area in mm^2, standard features in Rhinoceros. Assessment of radial head concavity was a visual assessment using heatmap projected over the radial head articular surface.

The head/neck ratio as described by Kim et al[27] was calculated on plain radiographs for both missed Monteggia patients and their controls, and then compared to Q3DCT data.

Statistical analysis

Categorical variables are reported as frequencies and percentages, and continuous variables as mean with standard deviation (SD). We used a paired t-test to assess differences in outcome measures between cases and controls. A two-tailed p-value below 0.05 was considered statistically significant. To assess correlation, a Pearson correlation coefficient was calculated. IBM SPSS Statistics 25 was used for all statistical analysis and there were no missing values for any of the variables.

Results

Fourteen pediatric patients with a missed Monteggia lesion were eligible for inclusion. One patient denied participation, one patient had a potential congenital component (dysmorph radial head on the contralateral side) and two patients had preoperative CT scans of insufficient quality. Hence, ten patients could be included for Q3DCT analysis.

Average age of included patients was 11 years, range (5,9 to 15,5 years), there were six girls and four boys. The mean time between trauma and the CT-scan at presentation was 3,2 years (0,3 - 9,3) (table 1). Mean follow-up was 1,7 years (0,8-5,8 years).

Table 1. Patient characteristics. M/F = Male/Female; Trauma-CT=time between trauma and CT scan in years; H/N MM=Head/Neck ratio; def=deformed; cap. overgr.=caput overgrowth; H/N C: Head/Neck ratio Control; ns=Not specified. Note: case A and B are patients that were treated conservatively.

Case no	Side	M/F	Trauma-CT(y)	Age at CT(y)	H/N MM	Age at Surg(y)	Intraoperative Aspect	Repositioning	Complications
1	R	F	2.2	9,3	1,81	9,45	30-40% def.	easy	
2	L	F	2.1	7,7	1,41	7,59	Mild def. cap. overgr.	Impossible	
3	L	F	ns	5,9	2,21	15,55	Slight def.	Easy	non-union with redislocation
4	R	F	0.3	11,3	1,4	11,69	Bipolar def.		
5	L	F	5.4	12,0	1,43	12,18	Some def.	Impossible	
6	L	M	5.8	12,5	1,52	13,04	Slight def.	Easy	
7	R	M	0.4	12,3	1,5	12,58	Slight def.	Easy	subluxation
8	L	F	1.1	7,7	1,53	8,07	Slight def.	Easy	
A	L	M	9,3	15,4	1.97				
B	R	M	2,0	15,5	1.64				
Mean			3.2	9.8	1.64	11.3			

1 2 3 4 5 6 7 8 9 10 AI AII AIII AIV AV AVI AVII AVIII

Indications for elbow CT-scan in control patients were: olecranon trauma (n=3), medial extraarticular calcifications (n=2), medial condyle fractures (n=1), supracondylar fracture (n=2), radial neck fracture (n=1) and Osteochondritis Dissecans of the capitellum (n=1).

The mean age difference between the included patients and their age/sex matches was 0,02 year (range 0 - 0,4 year). (table 2).

Table 2. Radial head volume and articular surface area of the radial head in Missed Monteggia lesion patients versus age and sex matched control cases.

	Missed Monteggia Cases (n=10)	**Controls (n=10)**	**p-value**
	Mean (±SD)	**Mean (±SD)**	
Volume of the radial head in mm3	1487 (±1180)	1163 (±836)	*0.317*
Articular surface area of the radial head in mm2	282 (±143)	236 (±128)	*0.331*

Eight patients underwent a surgical correction of the chronic radial head dislocation (cases 1-8 in table 1). There were two complications (case 3: ulna non-union and redislocation of the radial head, and case 7: subluxation of the radial head). Two patients were treated conservatively (case A and B) because the surgeon considered the radial head too dysplastic on preoperative radiographs and CT-scans.

Radial head volume analysis

The volume of the radial head was not significantly larger in missed Monteggia patients compared to the control group (1487 mm^3 vs 1163 mm^3, p=0,32). There was no correlation between the trauma-CT interval and radial head volume (Pearson test, r=0,65 p=0,64), or the articular surface size of the RH (r=0,54 p=0,14).

Articular surface size analysis

The radial head articular surface size was also not significantly larger in missed Monteggia patients compared to the control group (282 versus 236 mm^3, p=0,32). Unfortunately, calculations of the percentage of the articular surface that was concave, turned out unreliable.

Heat map articular surface analysis

The articular surface of the radial head was depicted in a heat map using Q3DCT (Figure 1). Some heat maps of patients that were either not operated due to suspicion of radial head dysmorph changes on a plain radiograph (cases A and B); or of patients that sustained a redislocation (case 3 and 7) appeared flattened or convex. However, Q3DCT heat map images could have a similar flattened aspect in the control group. A supplement is available that contains an overview of all MM and C heat maps. Optically, there were no evident differences in articular surface shape for cases versus controls.

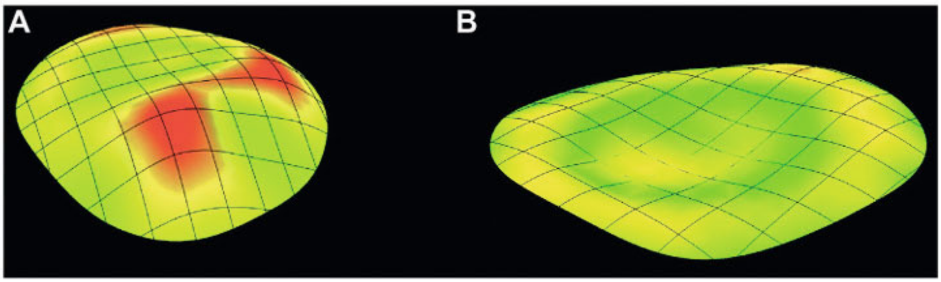


Figure 1. Heat map image of the radial head articular surface relief (case 4). A: Missed Monteggia patient; B: age/sex matched control.

Comparison to the Head/Neck ratio

The head-neck (H/N) ratios in patients with missed Monteggia lesions were significantly higher than in the control cases (mean H/N ratio in missed Monteggia was 1,64 and mean H/N ratio for controls was 1,40; p=0,048). We also found a significant correlation between the head-neck ratio and the radial head volume in missed Monteggia patients (Pearson r=0,73; p=0,02).

Discussion

This study describes a small cohort of missed Monteggia patients, whose radial head was examined using Q3DCT. Currently, the assessment of preoperative radial head deformation is subjective; Q3DCT seemed a promising and easily accessible method to quantify the amount of radial head deformation.

Unfortunately, measurements of the concavity of the radial head turned out to be unreliable, and the interpretation of a heat map of the articular surface is highly subjective. Its value is therefore still debatable in individual cases. Our cohort was thereby too small to be able to make any statement regarding the intraoperative aspect of the radial head and Q3CT heat map images, and the value of statistical analysis is limited due to the small number of patients. Future research should be prospective and should contain a CT-scan of the contralateral elbow. Also, an inter- or intra observer evaluation would be interesting to assess the clinical value of Q3DCT heat map images.

Multiple factors are of influence on the stability of the radial head. Pulling forces of surrounding muscles[34] or the interosseous ligament may play a role[11,12,17,35-37]. A (posttraumatic) length discrepancy between the radius and ulna may also interfere with tension on the radial head and hence complicate radial head reduction[38] The ulna non-union in one of the cases that experienced a redislocation hence may have had more influence than the shape and size of the radial head. Dysplastic changes to surrounding bony structures, such as the Radioulnar joint and the capitellum, may also be of interest[26]. Dysplasia of the radial head is hence just one of several factors that may lead to a redislocation following surgery for missed Monteggia lesions.

In literature, many authors discuss the time between injury and surgery and the age of the patient in the workup to surgery. Some indicate a maximum age for surgery (potentially because less remodelling is possible at older age)[39,40], others indicate a maximum time between injury and surgery because the dysplastic radial head changes may increase over time[41,42]. In this study, there was no correlation between time since trauma or the age of the child and the volume of the radial head, like in several other publications[6,18,23,43]. We advise that in every individual case, an assessment of radial head dysplastic features should be made regardless of the time since trauma or patient age. However a study with a larger cohort is necessary to be able to adequately test this statistically.

Conclusions

There were no significant differences in Q3DCT calculations for radial head volume and articular surface size between missed Monteggia patients and age/sex matched control cases. A heat map analysis of the radial head articular surface showed no specific differences in articular surface shape compared to the control group. A higher head-neck ratio was correlated to higher Q3DCT radial head volumes. Q3DCT may still be an interesting tool in the preoperative workup for missed Monteggia patients, but prospective research that combines preoperative, intraoperative and postoperative findings in a larger case series that includes contralateral CT scan analysis is mandatory to assess its clinical potential.

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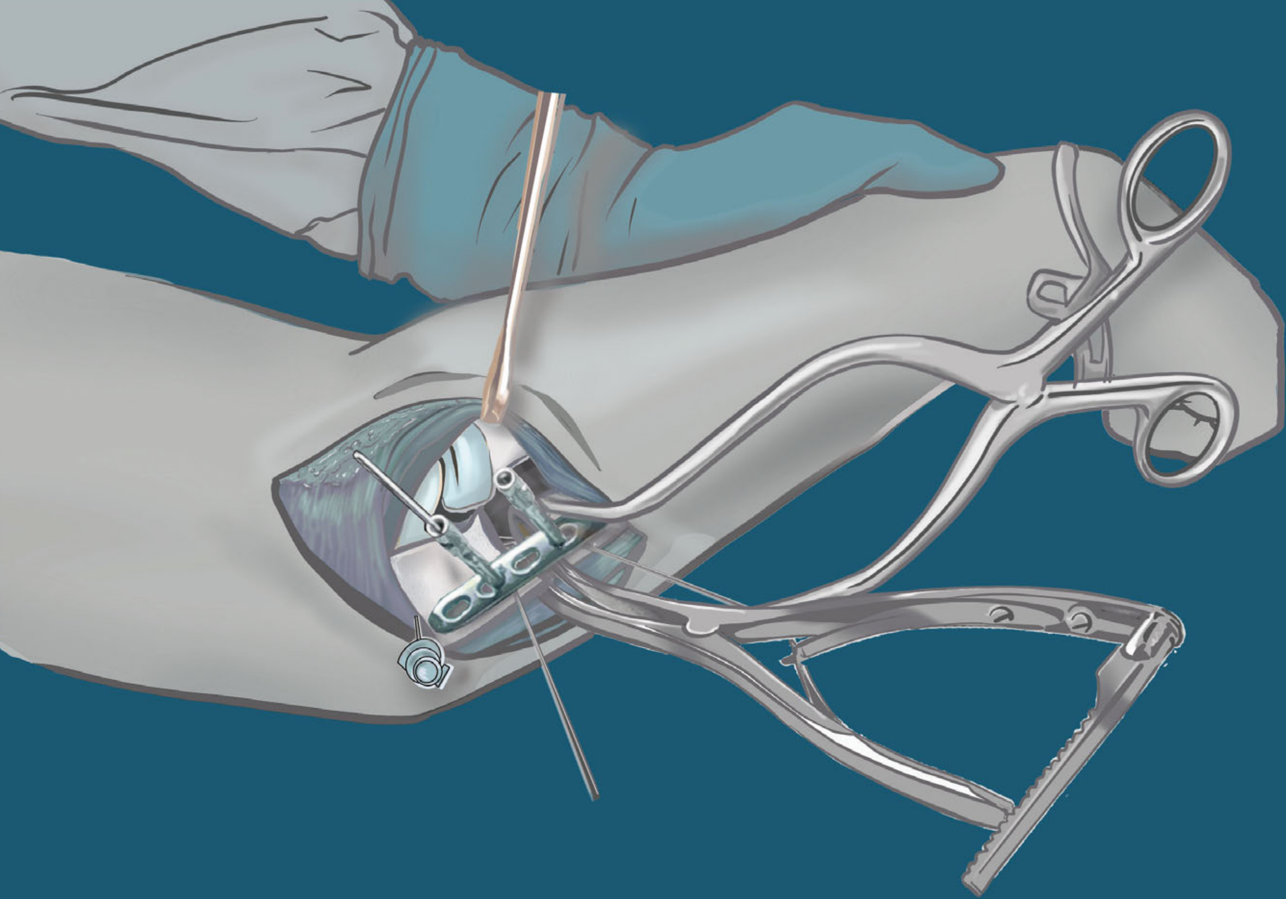

CHAPTER 07

Surgical treatment of chronic radial head dislocations in missed Monteggia lesions in children;

a rationale for treatment and pearls and pitfalls of surgery

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Published, Shoulder Elbow, 2020 Dec;12(6):422-431.
doi: 10.1177/1758573219839225.

Abstract

Introduction The treatment of chronic radial head dislocations after Monteggia lesions in children can be challenging. This article provides a detailed description of the most frequently performed surgical technique: an ulna osteotomy followed by annular ligament reconstruction. Accordingly, we present the clinical and radiological results of 10 pediatric cases.

Material and methods All pediatric patients that had a corrective osteotomy of the ulna for a missed Monteggia lesion between 2008 and 2014 were evaluated with standard radiographs and clinical examination. A literature search was performed to identify the relevant pearls and pitfalls of surgery. Primary outcome was range of motion.

Results We included 10 patients, with a mean follow-up of 2.5 years. Postoperative range of motion generally improved 30.7°. Even in a patient with obvious deformity of the radial head, range of motion improved after surgery, without residual dislocation of the radial head.

Conclusion Corrective proximal ulna osteotomy with rigid plate fixation and annular ligament reconstruction yields good results in patients with chronic radial head dislocation following a Monteggia lesion. Surgery should be considered regardless of patient age or time since trauma. Given substantial arguments in literature, we discourage surgery if a CT scan shows dome-shaped radial head dysmorphic features in work-up to surgery.

Keywords: annular ligament reconstruction; chronic radial head dislocation; monteggia; posttraumatic radial head dislocation; ulna osteotomy.

Introduction

Although most children with a radial head dislocation are at first asymptomatic, complaints may arise over the course of years. Pain, loss of range of motion (ROM) and neurologic complaints can occur, primarily because of scarring, chronic compressive changes, or due to nerve entrapment in the (sub)luxating joint(1,2). In the growing child, long-standing radial head dislocation may thereby cause deformity of the radial head, overgrowth of the proximal radius, instability and early osteoarthritic changes of the elbow joint (3–7). Furthermore, the ulna is relatively shortened, which may lead to complaints at the level of the wrist. Therefore, reduction of the radial head should take place as soon as possible to prevent these long-term harmful effects(1,4).

Mechanism of injury and the effect of growth

If a Monteggia fracture occurs, the interosseous membrane ruptures. Consequently, tension on the radial shaft and radial head reduces, allowing it to dislocate. This mechanism explains why over 70% of radial head dislocations is in an anterior direction (Bado type I). Several articles that describe the trauma mechanism for a Bado type I Monteggia fracture have been published, which render different explanations(8–10). Secondly, the annular ligament may rupture or dislocate from the radial head, and migrate into the proximal radioulnar joint, interfering with reduction of the radial head(3,6,11,12). Finally, during growth, ulnar angulation may develop(4,13,14), which may result in a persisting dislocation of the radial head. Treatment ideally should address all components of the injury; providing reduction of the radial head, correction of ulnar length and angulation, and reconstruction of the annular ligament(11,15,16).

Surgery for posttraumatic chronic radial head dislocation may include an ulna osteotomy, for which there are several ways of fixation, and/or annular ligament reconstruction. Reduction of the radial head can be achieved by an open approach or without opening the joint(17–20). No consensus has yet been reached regarding the necessity for the several steps in this surgical procedure. Workup to surgery is thereby also still unclear; it is unknown whether dysmorphic features of the radial head are a contraindication for surgery or whether time between trauma and surgery is of influence on surgical outcome. In this article, we will therefore outline the work-up, treatment rationale and several pearls and pitfalls of the surgical technique. We will thereby describe the clinical and radiological outcome for range of motion in ten pediatric cases.

Materials and Methods

We composed a patient cohort consisting of all consecutive patients undergoing a corrective osteotomy of the ulna between 2008 and 2014, for chronic radial head malalignment following a Monteggia lesion. A radial head dislocation was considered a chronic lesion four weeks after sustaining a trauma(4,6,21,22). Congenital dislocations were excluded.

Patient follow-up consisted of a physical examination and a radiological assessment. Radiological check-ups were performed conform to local protocols.

Workup to surgery

Ideal timing of surgery has been widely discussed in literature, and opinions vary. We decided to use each patients amount of radial head deformity as a guideline. Several authors regard the chances of successful surgery low if the concavity of the radial head has been completely lost (3,16,23). These studies identified that the amount loss of concavity of the radial head directly determines surgery outcome more so than patient age or time since trauma.

Prior to surgery, a CT scan is deemed essential to assess the degree of radial head deformity. Dysplastic changes of the radiocapitellar joint are identifiable on a CT scan, and the process enables the construction of a 3D model (14,24). In cases where the patient is a young child with considerable residual growth and potential for remodeling (15,25), an MRI may be preferable.

In two patients that were seen in our hospital, radial head deformation had developed to such extend that the radial head had lost its concavity and as such, we decided not to perform surgery. In both patients, an exceptionally prominent dome-shaped radial head was noted, with a slender radial neck. (Figure 1A-1C).

Figure 1. (a to c). Persistent radial head dislocation seven years following Monteggia lesion (head–neck ratio 2.2).

Alternatives for surgery in these cases consist of follow-up and planning of radial head excision if elbow complaints persist after bone maturity has been reached. However this procedure is considered as salvage surgery(7). In a patient seen at our hospital, follow-up of a dome-shaped radial head lasted seven years (Figure 1). The patient had fallen of a slide at the age of seven years, and the elbow had initially been immobilized in a cast without recognition of the radial head dislocation. Four years following trauma, complaints of pain and restrained elbow flexion arose. Upon presentation in our hospital 6 years after trauma, there was a prominent, palpable radial head and a restriction of elbow ROM with a positive anterior impingement test were noted (flexion 100, extension +10, pronation 30 and supination 45 degrees). On examination at last follow-up, no pain was present, but the patient experienced crepitations in the joint. An evident cubitus valgus was seen (estimated 25 degrees), and ROM, mostly supination, was impaired (flexion 110, extension +10, pronation 70 and supination 45 degrees). A “watchful waiting” policy is now initiated, to evaluate the patients’ complaints while the skeleton matures.

In cases of deformation with preserved concavity, to date no tool has been installed to relate radial head deformation to surgery success rates. Kim et al described a head-neck ratio (14, figure 2A-2C). However, they were not able to identify the consequences of a higher ratio, other than that the surgeon had to be aware of a more difficult reposition of the radial head due to anatomical anomalies.

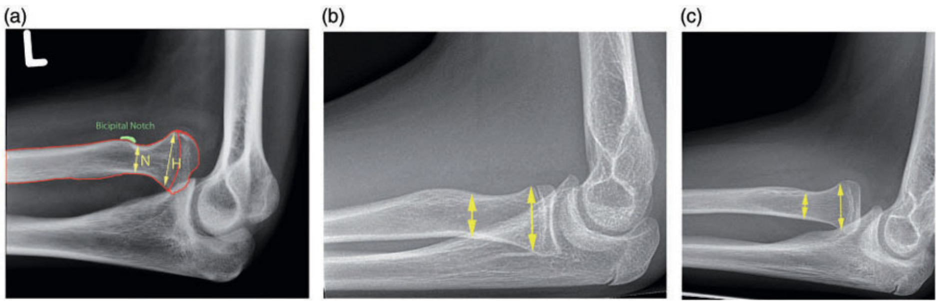

Figure 2. (a) Head/neck ratio. H/N; H¼metaphyseal diameter measured at the widest part adjacent to the physis, N¼neck diameter measured at the narrowest past proximal of the bicipital notch. **(b)** non-affected side (head/neck ratio 1.6); **(c)** affected side 2C (head/neck ratio 1.9)

Surgical Technique

All operations were performed by two orthopaedic surgeons (DE and BT). Patients were operated under general anaesthesia, in a supine position. First, the proximal radioulnar joint (PRUJ) was opened using a lateral incision (Kaplan incision). The joint space of the PRUJ was debrided and annular ligament remnants were identified and preserved where possible.

The ulna was approached using the same incision that gave access to the PRUJ. A wedge osteotomy of the ulna at the most proximal site possible was performed, adapting ulna length and angulation under radiologic guidance until radial head reduction was achieved. After radial head reduction, rigid plate fixation of the osteotomy of the ulna was performed with a Locking Compression plate (LCP). The plate was bent if necessary. We used 3.5mm locking head screws for fixation. Fluoroscopy was used to determine the level of the osteotomy and the optimal placement of the plate and screws, avoiding interference of the screws with the growth plate of the proximal ulna. No bone grafts were used. Thereafter an annular ligament reconstruction was performed, using annular ligament remnants when possible. Alternatively, reconstruction was performed by using a piece of triceps fascia, that was attached with trans osseous sutures.

Finally, elbow range of motion (ROM) and radial head stability were assessed postoperatively, while the patient was still under general anaesthesia. A radioulnar K-wire was placed to secure the radial head reduction if the surgeon preferred to support radial head stability. This K wire was placed distally to the PRUJ to prevent damage to the cartilage, and was then removed after four weeks.

Patients were immobilised for six weeks in an above elbow cast in 90° flexion, with the forearm in a neutral position following surgery. Active forearm rotation, elbow flexion and extension were allowed at six weeks postoperatively. Plate and screws were removed routinely 6-12 months after surgery. Figure 3A shows a preoperative X-ray of the elbow in a patient that had sustained a Monteggia injury two years prior to presentation at our hospital. Figure 3B depicts the X-ray of the situation directly after ulna osteotomy and annular ligament reconstruction, and figure 3C shows the outcome 1.5 years after surgery.

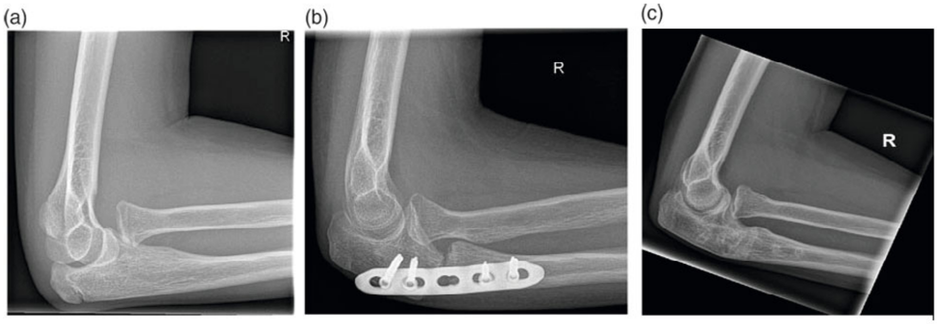

Figure 3. (a). Preoperative X-ray of the elbow in a patient that had sustained a Monteggia injury two years earlier; **(b)** X-ray of the elbow six weeks after ulna osteotomy and annular ligament reconstruction; **(c)** outcome 1.5 years after surgery.

Results

Case series

Mean age at surgery was 8.2 years (range 5.3 – 12.7 years). Mean interval between injury and surgery was 1.8 years (range 0-4 years). All dislocations were Bado type I (anterior). In four patients, the initial diagnosis had been missed on presentation. Detailed patient characteristics are described in Table 1.

Intraoperative findings

Intraoperative testing of the ROM under general anesthesia did not notably differ from preoperative clinical findings. In four patients, we noted that the severity of radial head deformation on x-ray (head-neck ratio calculated following Kim et al(14)) and on intraoperative inspection did not correlate. No relationship was identified between the time since trauma and surgery, patient age or previous surgery. For example, the patient that had the longest time to surgery (four years), had a head-neck ratio of 1.8 and only mild deformation of the radial head on intraoperative inspection.

Postoperative Range of motion

In all cases, the radial head was stable on direct postoperative stability testing under general anaesthesia. Follow-up was 30.4 months on average (median 59 months (707 days); range 2.3 – 94.1 months). One patient was lost to follow-up (table 1: patient nr. 7).

All osteotomies had healed within 6 months, which was demonstrated by standard radiographs. One child that had experienced complaints of a transient dropping hand after previous surgery around the proximal radius, reported a transient recurrence of the radial nerve palsy following surgery (patient 5). No other evident complications were reported.

Postoperative ROM (Table 2) increased overall with 30.7 degrees. No explanation was identified for differences in outcome between patients. No relationship was established between ROM outcome and radioulnar pinning, previous surgery, time between trauma and surgery, or age at time of surgery. Similarly, preoperative parameters such as radiological deformation or dysmorph features of the radial head on intraoperative inspection had no influence on ROM outcome.

Table 1. Patient characteristics

Pt nr	Lesion	Intraoperative radial head description	Head-neck ratio	Previous surgery	Age at time of trauma	Time trauma-surgery*	Affected side
1	Missed Monteggia	Mild deformation, caput magnum	1,8	2; no details short after trauma	5	4 years	dominant
2	pers. RHD	Mild deformation, Reduction impossible	1,5	None	11	1 year	non-dominant
3	Re-RHD following ulna osteotomy	Mild deformation, reduction possible	1,5	Ulna osteotomy, pen fixation 1 year after trauma	5	2 years	non-dominant
4	Missed RHD	Obvious deformation Reduction unstable	1,5	None	6	1,5 month	dominant
5	Monteggia	Mild deformation Reduction possible	1,6	None	4	1 year	non-dominant
6	Missed Monteggia	Mild deformation Reduction possible	3,2	Ulna osteotomy External fixation 1,5 year after trauma	3	3 years	non-dominant
7	Monteggia	Obvious deformation, Diameter discrepancy in pronation		Ulna osteotomy plate fixation	8	2 years	dominant
8	Missed RHD	Mild deformation (30-40% caput) Reduction possible		Open reduction Percutaneous fixation 6 months after trauma	8	2 years	dominant
9	pers. RHD	Mild deformation Reduction possible	2,1	None	No trauma recalled	No trauma recalled	dominant
10	pers. RHD	No information	1,8	none	11	2 years	dominant

RHD: radial head dislocation; * Time between trauma and surgery in our hospital

Table 2. Range of Motion. Kwire RU: radioulnar fixation. ΔROM=overall number of degrees increase in motion

Pt nr	K-wire	Pronation			Supination			Flexion			Extension			Overall ΔROM
		preop	postop	difference	preop	postop	difference	preop	postop	difference	preop	postop	difference	
1	RU	45			45	60	15	120	145	25	10	0	10	
2	RU	70	75	5	80	80	0	125	145	20	3	10	-7	18
3	RU	60	60	0	45	60	15	130	120	-10	0	20	-20	-15
4	None	45	70	25	20	80	60	95	130	35	-45	-15	30	62
5	None		60			70		120	110	-10	10	0	10	
6	None	“full”	“full”	0	“full”	“full”	0	“full”	“full”	0	“full”	0	0	0
7	None	70			70			125			-10			
8	None	60	70	10	50	90	40	100	145	45	0	0	0	95
9	RU	“full”	“perfect”	0	“full”	“perfect”	0	150	“perfect”	0	5	“perfect”	5	5
10	None	80	70	-10	30	60	30	120	140	20	-10	0	10	50
			mean	+4,3		mean	+20		mean	+13,89		mean	+4,22	+30,7

Discussion

Postoperatively, ROM generally increased in our case series. Three patients noted a decrease in either pronation, flexion or extension. The majority of other studies found an occasional decrease in pronation (3,5–7,11,22,26–30), and flexion generally increased. However, no explanations formerly noted in literature, such as time to surgery or amount of radial head dysplasia, seemed to be of any influence for the patients in our cohort.

We note that if the radial head is found to be dome-shaped, and has lost all its concavity, surgery tends to be unsuccessful. This is supported by convincing arguments (3,7,12,15,31,32). Even though we did not find radial head deformation influenced the outcome, we maintain that a CT-scan is mandatory in preparation for surgery.

Unfortunately, our cohort was too small to perform a statistical analysis. Questions regarding preoperative patient characteristics and their influence on outcome may be answered by performing a literature review with pooled data.

For each step in surgery, a number of "pearls and pitfalls" were identified following our literature search (table 3). These are elaborated in the following paragraphs.

Table 3. Pearls and Pitfalls

	Pearls	Pitfalls
Ulna osteotomy position and technique *We suggest a closing wedge osteotomy, placed as proximal in the ulna as possible*	Several authors described a stable situation following ulna osteotomy and fixation only. Osteotomy as proximal as possible: - potentially increases grip due to wider metaphysis in proximal ulna - Interosseous ligament pulling forces are increased - metaphyseal bone healing is overall better Angulation at the metaphyseal level has less effect on reduction, but it permits a finer adjustment. Lengthening of the ulna is necessary to avoid excessive pressure on the radial head.	Closed wedge osteotomy may lead to neurological impingement Transverse osteotomy (not bending/ elongating) may be associated with a higher risk of radial head redislocation An osteotomy at the center of rotation and angulation may predispose to non-union

Table 3. *Continued*

	Pearls	Pitfalls
Ulna osteotomy fixation *We suggest rigid fixation (LCP plate and locking screws)*	Rigid plate fixation: - facilitates early mobilisation - no need for interposition graft According to the tension band principle a posterior plate may be preferred. External fixation with multidirectional clamps simplifies the attainment of the most satisfactory position of the ulna since the system can be easily adjusted until a stable reduction has been achieved Intramedullary / radiocapitellar nailing (e.g. Steinman pins): - relatively easy pin removal	Plate removal will be necessary in young patients A lateral location of the plate for ulna fixation may be associated with nonunion. An external fixator: - may result in soft tissue contractures - may be less sufficient in a young child - requires multiple frame adaptation under general anaesthesia - may be associated with a higher risk of infection Osteosynthesis materials may break Unfixed ulna osteotomies are associated with high risk of radial head redislocation Pins may migrate or break. Pin infections are rare.
Annular Ligament Reconstruction (ALR) *We suggest to use remnants if possible, or a triceps graft when not available*	ALR may contribute to radial head stability Inspection and debridement of the proximal radioulnar joint is possible A triceps graft may be harvested via the incision that had been used for ulna osteotomy	ALR only cannot stabilise the radial head if the forearm is malaligned The use of drill holes may lead to heterotopic ossifications Use of forearm fascia for ALR may lead to a reconstruction that's too weak. ALR has been associated with postoperative loss of pronation Osteolytic changes may be seen; too much tension in ALR may cause hourglass deformation of the radial neck
Transcapittellar K-wire *We suggest that no transcapittellar K-wires should be required following a stable reconstruction. When in doubt, we prefer the use of a radioulnar K-wire.*	K-wire fixation may contribute to radial head stability Radioulnar K-wire fixation: - prevents damage to joint surfaces	Radioulnar K-wire fixation may cause heterotopic ossifications interfering with pro-/supination Migrating material Material fracture

Open versus closed reduction

Open reduction of the radial head has several advantages; even in repositioned radial heads, annular ligament remnants may interpose in the radiohumeral joint(33). In our series, we also noticed that radial head reduction may be hindered by interpositioning remnants of the annular ligament or fibrosis. Another argument for an open reduction is that the posterior interosseus nerve (PIN) may be incarcerated in the PRUJ or radiocapitellar joint (RCJ) (3,6,12,22). On the contrary, successful closed radial head repositioning has been documented by some authors (17–20).

Ulna osteotomy

Many authors described a stable situation following ulna osteotomy, in which subsequent annular ligament reconstruction was not always necessary(3,4,11–13,15,16,22,29,34–36). We aim for an osteotomy location approximately 1cm distally of the coronoid process, so the osteotomy location is as proximal as possible without opening the joint(4,11,16). This enforces the downward pull of the interosseous membrane, which contributes to repositioning of the radial head(11,16,23,37). In our experience, planning the osteotomy as proximal as possible also provides the advantage of a wider bone diameter in the proximal part of the ulna, resulting in a firmer grip and a larger contact surface. Thereby, metaphyseal bone has a higher potency for bone healing than diaphyseal bone. Angulation at the metaphyseal level has less effect on reduction, but it permits a finer adjustment(38). Several authors state that the risk for radial head redislocation is higher in osteotomies that were performed at the middle of the ulnar shaft(4). An osteotomy at the centre of rotation and angulation may predispose to non-union(38).

Ulnar lengthening may be considered a key part of surgery(31). Restoring ulnar length avoids excessive pressure on the radial head(4) and corrects the proximal shift of the radial head(7). The osteotomy may be planned either straight, oblique or as a Z-lengthening ulna osteotomy(37). Several authors conclude that the risk for postoperative redislocation of the radial head is lower following bending and lengthening ulna osteotomy than in a simple transverse osteotomy of the ulna, intended to only straighten the ulna(4,25). This slight overcorrection is considered to result in extra tension on the interosseous membrane, facilitating reduction of the radial head(26,32).

Acute ulna lengthening of up to 1 cm has been supported by others despite the risk of delayed union and failure of fixation(23,31). In most cases acute ulnar lengthening of 2 to 3 mm is sufficient and does not delay osseous union. One of the pitfalls when lengthening the ulna, is that osteotomy site distraction may lead to ulnar nerve palsy in a high percentage of cases(21). We affirm that the ulna should be lengthened and bent to a slight overcorrection, until the radial head repositions.

Ulna fixation techniques

We favor rigid fixation using a plate and locking head screws. One of the advantages of rigid fixation is that mobilization is facilitated and postoperative contractures prevented(4,22). Note that a lateral location of the plate for ulna fixation may lead to nonunion of the osteotomy. According to the tension band principle a posterior plate may be preferred(38).

Annular ligament reconstruction (ALR)

Some authors state that ALR has no effect on radial head stability at all(2). Others emphasize that ALR may contribute to stability of radial head reduction, but it cannot stabilize the radial head when the forearm is malaligned(13,29) and some even claim that ALR is the primary stabilisator in radial head reduction(4,31,39). Most authors agree that reconstruction of the annular ligament may contribute to radial head stability. Especially if there is persistent radial head instability when the forearm is brought to pronation after ulna osteotomy, ALR may be considered(15,20,28,30,40,41). Redislocations may occur more frequently if a patient only had an ulna osteotomy compared to patients that had an ulna osteotomy and a reconstruction of the annular ligament(5,6,12).

ALR has been associated with postoperative loss of pronation(5,26,28,30,42–44), especially if the annular ligament reconstruction is not properly tensioned. In a study performed by Rodgers et al, 2/6 ALR patients developed an hourglass deformation of the radial neck, which may occur if the ligament has been reconstructed with too much tension. Thereby 1/6 had ossification of a portion of the reconstructed annular ligament(5,21). Also, osteolytic changes may be seen following ALR(4,21,23,45–47), of which the clinical impact is still uncertain. Possibly adapted tension on the pronator teres muscle plays a role. We conclude that ALR may contribute to radial head stability and therefore we either sutured the AL remnants or used triceps tendon for reconstruction of the ligament.

Transcapitellar/radioulnar Kirschner wires

Most authors state that a transcapitellar K-wire may be considered if persisting instability is suspected after completing ulna osteotomy and annular ligament reconstruction(5,7,15,21,25,26,35,36,39,42–44,47–51). However, we favor radioulnar K-wire fixation, because it has the advantage that no joint surfaces are damaged. In our case series, we did not find any influence of this extra immobilization on ROM outcome.

It should be taken into account that heterotopic ossifications may occur, influencing pro- and supination; material may break, migrate, or on rare occasions material may infect(21,26,29,30).

In our cohort, one patient experienced a redislocation of the radial head following a reposition that had been previously fixated elsewhere with a radioulnar K-wire. If the radial head is prone to redislocate directly after surgery, this may mean that the initial reduction is not stable enough. No research has been performed to date to demonstrate that redislocation occurs more frequently if radiocapitellar pinning was necessary, but we state that in persistent instability, ulnar osteotomy should be reassessed and improved(29,52). As such, we would recommend radioulnar pinning in such case, as explained above.

Postoperative immobilisation varies greatly between several international studies. In a recent cadaver study, supination in the forearm increases tension on the central band of the interosseous membrane. Thus, forces pulling the radial head towards a repositioned state may be increased by applying a cast in supination(10). We however decided to apply an upper arm cast in 90 degrees, with the forearm a neutral position for patient comfort.

Conclusion

Our series show good results of an open radioulnar debridement, followed by corrective ulnar osteotomy, rigid plate fixation and annular ligament reconstruction. We note that adequate ulnar correction and fixation are the key to reducing the radial head, lengthening and bending the ulna until the radial head falls into place. An ALR or a radioulnar K-wire may contribute to stability.

Surgery should be considered regardless patient age or time since trauma. Within the ranges in our study, no influence of age nor interval since trauma could be found. However, future research should revisit this statement in a larger patient cohort that facilitates adequate statistical analysis. The extent of radial head deformation is concluded as a reliable guideline when deciding whether to operate on a patient in combination with a CT-scan as a mandatory part of work-up to surgery.

We emphasize that research is needed to establish preoperative tools in the workup to surgery. Patients and their families should be well informed about possible postoperative decrease in pronation, given the frequent reports of pronation impairment following surgery. We therefore recommend that the indication for surgery should be established in consultation with the patient and his parents, regardless of patient age or time since trauma.

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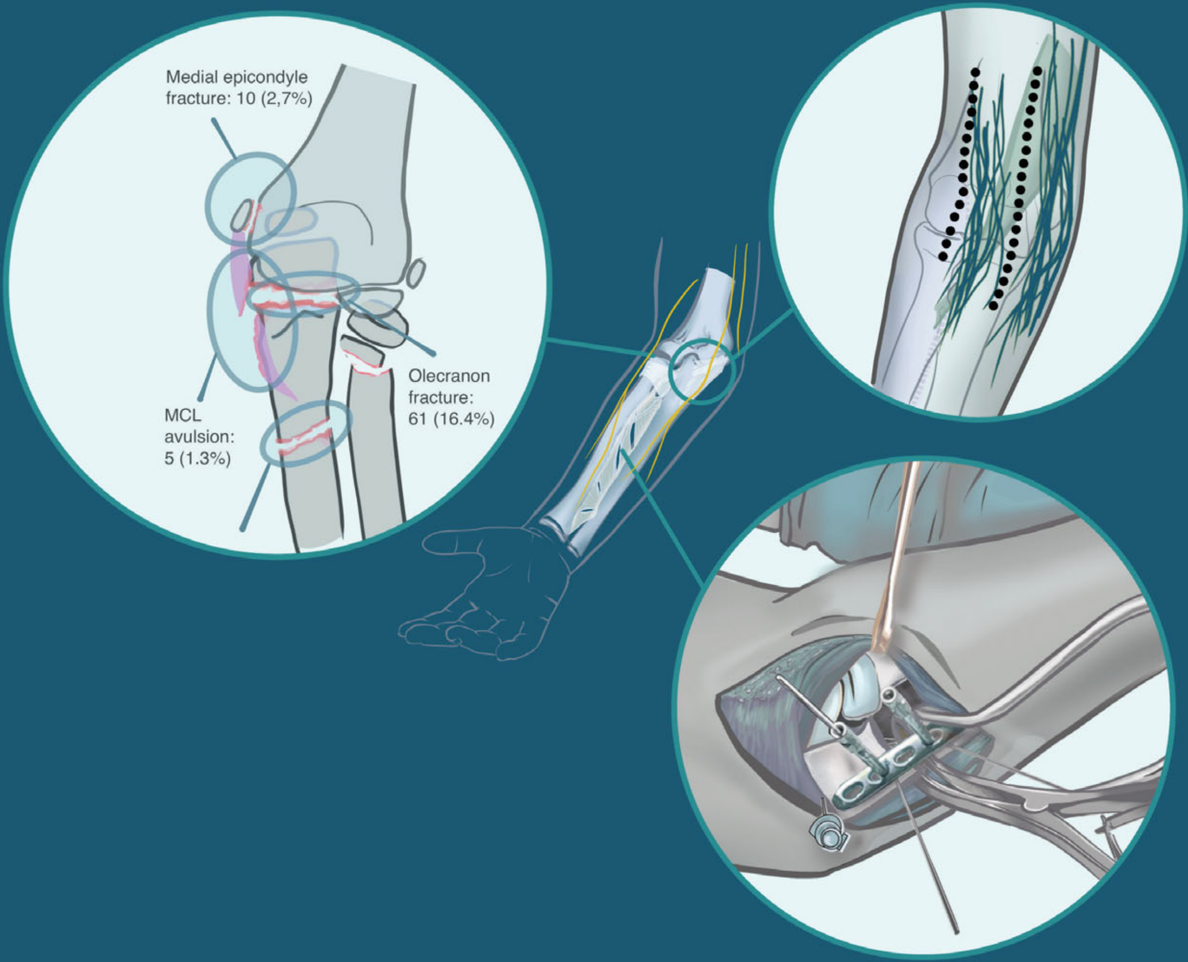

Medial epicondyle
fracture: 10 (2,7%)
Olecranon
fracture:
61 (16.4%)
MCL
avulsion:
5 (1.3%)

CHAPTER

08

Summary

Chapter one is a general introduction to this thesis, explaining the relevant anatomy, biomechanics and common injury patterns of the (pediatric) elbow. The potential effects of growth are discussed, and the pathophysiological pathway that may lead to posttraumatic sequelae and persisting loss of function in children is addressed.

Part one:

Detailed evaluation of anatomical variations of the cutaneous nerves around the elbow using Computer Assisted Surgical Anatomy Mapping (CASAM)

The first part of this thesis includes a meticulous study of the cutaneous nerves around the elbow. Sparing the delicate nerves that provide skin sensation around the elbow during surgery is of utmost importance to prevent painful neuromas or altered sensation of the skin. The sensibility of the lateral part of the forearm is mainly provided by the Lateral Antebrachial Cutaneous nerve (LABCN), which is formed by a branch of the musculocutaneous nerve which emerges from underneath the biceps tendon[1, 2]. The Medial Antebrachial Cutaneous nerve (MABCN) provides sensation of the medial part of the forearm, and mostly runs near and parallel to the basilic vein at the level of the elbow crease, or interepicondylar line[3]. Both nerves have a wide variety in their course and number of branches amongst individuals[4].

Depiction of small cutaneous nerves in anatomy books represents only one potential option of the course of these nerves. Ideally, surgeons should be able to plan their incisions in a “safe zone”, which contains the least amount of cutaneous nerve branches. CASAM is a technique that proved to be useful in the depiction of small nerves of various specimen in one summarizing stacked image[5]. In a wet lab setting, a grid is created, in which anatomical landmarks and structures of interest are marked. Subsequently it is possible to warp the images into one model using MagicMorph software, which respects the relative distance of anatomical structures and three-dimensional proportions of tissue. In **Chapter two**, the course of the MABCN is assessed in ten human specimen using CASAM. Injury to this nerve has been reported following surgical procedures on the medial side of the elbow, elbow arthroscopy, and even following small procedures like venipunctures. The incidence of MABCN injury following surgery may be underestimated, because it is not an item in most patient-reported outcome scales. Although the symptoms may be mild and self-limiting, examples of debilitating pain due to neuromas are described or even impairment in range of motion of the elbow. A large proportion of the patients who experience ongoing pain following ulnar nerve surgery, may in fact have MABCN-induced complaints. The aim of this study was to assess if there is a “safe zone” on the medial side of the elbow joint that does not contain any branches of the MABCN. All MABCN branches around the medial elbow are anatomically explored and marked in ten human specimen. Using CASAM, the average path of the Medial antebrachial Cutaneous Nerve (MABCN) was depicted. In 90 degrees flexion, there was a large variety of MABCN courses, with no clearly definable safe zone for surgical approaches. Being aware that there is no “safe zone” enables surgeons to perform their medial skin incision with caution not to damage the MABCN branches.

Both the LABCN and the MABCN are depicted using CASAM in **chapter three**. Traditional anterior skin incisions around the elbow like the Boyd-Anderson and Henry approach use anatomical landmarks without respecting the course of underlying cutaneous nerves. They are based on the internervous planes of deeper structures. The LABCN is also at risk in the surgical approach of the distal biceps tendon. In this paper, ten specimen of the human arm were used to identify the most common courses of cutaneous nerves around the elbow crease. The aim was to identify a zone that contained a minimum risk of cutaneous nerve injury (“safe zone”). One of the most important conclusions was that, if the Henry approach would deviate slightly lateral, the incision would run in the most lateral quadrant which was mostly free from cutaneous nerves. The Boyd-Anderson approach may be placed slightly further medially, but lateral to the basilic vein distally. This places it in the 2/4 medial zone, which does not contain cutaneous nerves. Both incisions should only be adapted in their superficial course, deeper structures should best be dissected in their internervous plane, as traditionally advised.

Part two:

Outcome of pediatric radial neck fracture

Chapter four elaborates on the incidence of associated injuries in pediatric radial neck fractures (pRNF). It has been presumed that different associated injuries are present in children older than ten years of age, as compared to those younger than 10, due to the hardening of the epiphyses with progression of growth. Also, several authors of previous literature on this topic state that increased angulation of the radial neck represents a more high-energetic injury. Chapter four provides a meta-analysis of 371 individual pediatric cases of pRNF which evaluates the incidence of associated injuries, like ulna fractures, ligamentous injury or elbow dislocation. There were 123 children with associated injuries (33.2%). Meta-analysis of our data showed that the incidence of associated injuries is not correlated to age or Judet classification. Olecranon fractures and other ulna fractures occurred most frequently. Surgeons may get a better impression of the severity of the elbow injury and the structures that are involved by deducing the trauma mechanism, than by using traditional classifications like Mason, Judet or O'Brien, which are based on radiographic criteria only.

In **chapter five**, the aim was to assess whether specific groups of pediatric radial neck fractures (pRNF) would benefit from a certain surgical treatment, especially in the group of pRNF with >30 degrees angulation (Judet types 3 and 4). Following a PRISMA-guided systematic review, data on Judet classification, type of treatment, duration of follow-up and range of motion were extracted from previously published case series. Type of treatment included open or closed reduction (OR or CR), Kirschner wire fixation (Kw) or closed intramedullary pin fixation (CIMP). The results imply that there is a slight advantage of Kw in the 30-60 degrees (Judet 3) group, compared to CIMP fixation, with regard to ROM at follow-up (Kw 9.7% impaired vs. CIMP 32.6% impaired, p = 0.01). In addition, in more than 50% of cases that required open reduction (OR), a loss of motion occurred.

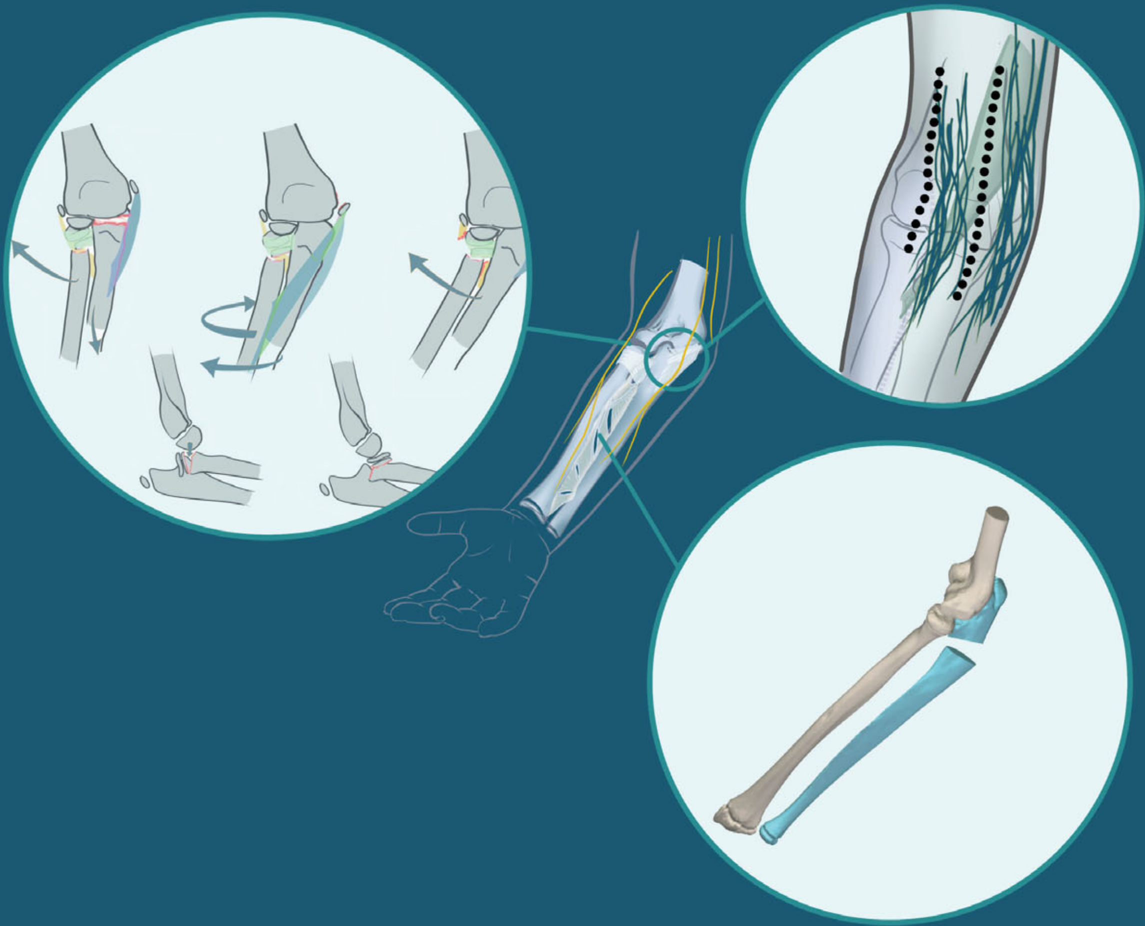
Part three:

Missed Monteggia injuries

Monteggia injuries are complex and frequently missed, and consist of an ulna fracture combined with a radial head dislocation. At first, the dislocated radial head may not induce any symptoms. However, over time, the radial head deforms due to lack of pressure on the articular surface, because of loss of contact with the capitellum. Complaints may arise, like decreased range of motion (especially flexion), neuropathies, valgus instability and pain around the radial head as a result of impingement of surrounding anatomical structures. Patients with a missed Monteggia injury therefore often present months to years following trauma, with a chronic radial head dislocation.

In **chapter six**, the workup to surgery for missed Monteggia injuries is evaluated in combination with description of a technique for 3D surface measurements of the radial head. Radial head deformation in missed Monteggia mostly includes widening of the head circumference and bulging of the articular surface, which becomes dome-shaped. If these dysmorphic features become so extensive that proper restoration of radiocapitellar articulation is impossible, corrective surgery is contraindicated. To date, there is yet no reliable tool for preoperative estimation of the amount of radial head deformity. In this study, the hypothesis was that exact calculations or radial head features using quantitative three-dimensional CT (Q3DCT) images, may be useful in assessing the deformity of the radial head. However, there were no statistical differences in articular surface size or percentage of concave articular surface between ten children with chronic missed Monteggia and age/sex matched control cases. Q3DCT also allows for the depiction of articular surface relief in a heat map. These heat maps may be of value because they provide a detailed visual of the articular surface for the surgeon. However, the interpretation of these images is subjective.

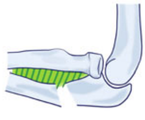
Corrective surgery for missed Monteggia lesions may comprise of a series of steps: Open or closed reduction (OR or CR) of the radial head, ulna osteotomy (UO), and annular ligament reconstruction (ALR). It is still uncertain if all these steps are necessary to obtain successful radial head reduction. Some claim that UO should only be performed if there are evident signs of bowing in the ulna, or if there is still instability following ALR. However, most authors state that UO is key, and that even overcorrection is necessary to prevent radial head redislocation. In **chapter seven**, a systematic search is performed that identifies all case series on missed Monteggia in children. Details regarding the surgical techniques were extracted and pearls and pitfalls are presented. A case series of ten patients further underlined the experiences with corrective surgery for missed Monteggia in children.



CHAPTER

09

General discussion



Historical concepts

Since the 50s of the last century, descriptions of fracture patterns and surgical approaches were developed. Mostly, they were named after the first surgeon who described them. The Henry approach, which is based on internervous planes, is an example. The combination of an ulna fracture and a radial head dislocation was named after Giovanni Batista Monteggia (1762-1815)[6], and classification systems for radial neck fractures were described likewise in several formats, like the Judet, O'Brien or Mason classification[7]. Many of these eponyms are still used today.

Evaluation of surgical techniques for complex forearm and elbow injuries started in the decades that followed, mostly by the publication of small case series, often in a retrospective design. Surgical techniques started evolving; for example, intramedullary techniques for radial neck fractures increased in popularity. At this time, an increasing number of case series was published, sharing treatment outcomes of different treatment options. There was a rising call for more evidence-based arguments for the choice of surgical treatment and more detailed evaluation of treatment outcome. More critical evaluation of treatment of complex elbow- and forearm injuries became possible, now that the number of case series increased. Statistic evaluation and even meta-analysis of subgroups became an option. In the current high-demanding society, optimising the work-up to surgery and treatment outcome are of high priority for the patients, their families and orthopaedic surgeons.

Optimising current concepts

1. Preventing cutaneous nerve injury

The course of the cutaneous nerves is known to vary among individuals. The number of branches and locations of bifurcations differ, and the exact course of the nerves is influenced by body composition. Although there are atlases full of anatomic variations, the small cutaneous nerves are often depicted in one potential position, at set distance to anatomical landmarks that are thus not applicable in every patient, especially not in children. Injury to cutaneous nerves may impair surgical outcome in several ways. Neurological complaints like altered sensation of the forearm have been reported, painful neuromas may form, and even range of motion may be diminished due to cutaneous nerve injury. Part one of this thesis focused on "modernising" the optimal superficial surgical approach to the elbow.

In children, evaluating subtle nerve injury is challenging due to multiple factors. History taking may be difficult or impossible, patient-reported outcome scales (PROMS) are mostly validated for use in adults, and answers to questions may be influenced by parents' or researchers' responses or interpretations. Because of this, obtaining an unbiased evaluation of the incidence of cutaneous nerve injuries in children will always remain difficult. It is, therefore, best to prevent injury to these nerves in every possible way.

The main goal of the studies in part one was hence to identify safe zones that may be found at relative distances compared to anatomical landmarks. This way, the estimated course of small cutaneous nerves may also be applied in children. By using a computer-assisted technique, the most common courses of these small nerves were depicted. One of the main conclusions was that fewer cutaneous nerve injuries could occur if the incisions for the traditional Henry and Boyd-Anderson approaches are shifted subtly.

Unfortunately, no safe zone without cutaneous nerve branches was present on the medial side of the elbow. This should raise awareness among surgeons, and careful dissection is paramount and magnification of the surgical field through the use of loupe glasses may be considered.

Future perspectives

Innovations that include augmented reality or the use of depiction of CT- or MRI images for the surgeon during surgery are upcoming. In the future, it may be interesting to use the outcome of CASAM to project safe zones on the patient when prepping for surgery. This may be possible by using visible or palpable landmarks for the surgeon, like the olecranon tip or the epicondyles, and then visualising the safe zones by projecting them on the patient or displaying them via augmented reality.

2. Improving evaluation of pediatric radial neck fractures

Radial head or neck fractures account for 5% of pediatric elbow injuries, in which 90% involves the radial neck or physis[8]. Dysplastic features of the radial head, lesser sigmoid notch and radiocapitellar joint may be seen many years following a pediatric radial neck fracture (pRNF), causing pain, impaired range of motion or early onset osteoarthritis. Treatment options at this stage are sparse due to degenerative changes, the high risk of avascular necrosis of the radial head in corrective osteotomies and the complex biomechanics and morphology of rotating parts in the forearm. Late sequelae are frequently seen following pRNF, and there are many examples of missed associated injuries, like ulna fractures, avulsions or dislocations. To date, there has not yet been much research that focused on these associated injuries. Traditional fracture classification systems like Judet, Mason or AO-classification do not include associated injuries. Only a small amount of studies aimed to address pRNF injury mechanism and its consequences for anatomical structures surrounding the elbow. There is a lack of knowledge on this topic.

In chapter four, the aim was to evaluate the presence of associated injuries. The idea that initialised this study was that missed additional injuries may substantially influence pRNF treatment outcome. Not in all case series, the presence or absence of associated injuries in pRNF is published, causing potential bias in the general interpretation of the results. By evaluating a select group of patients for whom these details were available, a better insight may be given into the incidence of associated injuries. Potentially, a group of children with a high risk for poor outcome following pRNF may be identified in an early stage, preventing late sequelae or early osteoarthritis, which is very challenging to treat.

A meta-analysis of individual patients with pRNF showed that associated injuries are present in 1/3 of pRNF, regardless of patient age or Judet grade. It was unfortunately impossible to draw conclusions regarding the influence of associated injuries in pRNF on treatment outcome. The choice of treatment for pRNF in the available case series was primarily based on surgeons' preferences. There is a large bias because of the heterogeneity in treatment algorithms, especially because the presence of associated injuries led to conflicting treatment choices. Some surgeons chose to treat every pRNF with associated injuries with an open procedure, while others emphasised that associated injuries were of no influence on treatment choice. Outcome may be worse following open surgery or due to more complex injury; it is hence impossible to distinguish between the two.

A theory that careful evaluation of the trauma mechanism may help predict the presence of associated injuries is explored in chapter four. A thorough literature study reveals that pRNFs are mainly caused by valgus injuries during axial load of the arm. Forced supination may thereby cause pronator pulling forces with medial (epicondyle) avulsions, and specific injury patterns may be seen following elbow dislocations. Recognising these injury patterns may reveal a specific group of patients requiring a more intense follow-up; for example, children who experienced a dislocation may have poor results due to elbow stiffness.

Currently, the consensus in literature is that pRNFs may be treated conservatively up to 30 degrees of radial neck angulation (Judet 1 or 2). If radial neck angulation exceeds thirty degrees, intervention is advised, but there is yet no consensus on which treatment is the most successful. There are several options: closed reduction (CR), followed by cast immobilisation without fracture fixation, percutaneous Kirschner wire fixation (Kw), intramedullary pinning (CIMP), or open reduction (OR), with or without fracture fixation.

In chapter five, individual patient data was used to evaluate the effect of these treatment options on outcome after at least one year. Data was stratified according to Judet classification; under 30 degrees pRNF angulation, 30-60 degrees angulation, and more than 60 degrees angulation. The primary outcome was range of motion (ROM). The main reason for choosing this modality was that reporting of PROMS was very heterogeneous; in 26 articles, over fifteen different outcome measures were used.

We found no significant differences in outcome for Kw versus CIMP treatment for the <30 and 30-60 degrees angulation groups. In the pRNF group with more than 60 degrees radial neck angulation, there was a slight advantage of Kw fixation over CIMP. There may have been a selection bias, a publication bias or bias due to the presence of associated injuries; a well-designed randomised control trial (RCT) will be needed to verify this finding. However, there will be several challenges to address which may delay the setup of such a trial, like difficult medical-ethical dilemmas regarding comparative studies in young children, and the effort required for performing elbow stability tests or additional radiologic examinations which require general anesthesia.

Future perspectives

With the new knowledge that associated injuries are present in 1/3rd of pRNF, there is a call for a classification system that includes injuries to ligaments, bones and soft tissues surrounding the elbow. However, as pointed out before, history taking and adequate physical examination may be unreliable in small children; it is questionable if deduction of the trauma mechanism will be feasible in pediatric patients. Future research could aim to provide an objective method to diagnose associated injuries. Potentially, the use of ultrasound for identification of associated injuries in pRNF may be an interesting modality to study in future research. Furthermore, the injury mechanism for elbow dislocations in adults has recently been reviewed, analysing film clips of the trauma. It revealed that there is at first a forced hyperphysiologic valgus motion [Schreiber], which changed the interpretation of the injury mechanism for elbow dislocations in adults [Singh]. A study that aims to retrieve video footage of the injury mechanism for pRNF in children could therefore be an interesting suggestion for future research.

3. Improving surgical treatment of pediatric missed Monteggia injuries

It is essential to realise that there is a substantial biomechanical difference between Monteggia injuries and pRNF (with or without associated injuries). A Monteggia injury is a complex forearm injury which consists of a radial head dislocation in combination with a fracture or bowing of the ulna. In forearm injuries like Essex-Lopresti, Galleazzi or Monteggia injuries, there is a longitudinal radio-ulnar discrepancy (LRUD), which involves injury to the interosseous membrane (IOM)[9]. In all cases, it is eminent to exclude the possibility that there is a congenital radial head dislocation, in which surgical reduction of the radial head is deemed to be unsuccessful. Suspicion of a congenital radial head dislocation should be high if there is a bilateral dislocation, if dysplastic changes of radial head, capitellum and PRUJ are extensive, or if there is no (radiological) history of trauma. About 50% of congenital dislocations are bilateral[10].

A high percentage of pediatric Monteggia injuries is missed at initial diagnosis (20-50%[11]). Thereby, up to 20 percent of the Monteggia injuries that are treated with an initial radial head reduction has a secondary dislocation of the radial head (re-dislocation) [12]. Either the radial head dislocation is not noticed, and solely the ulna fracture is treated, or there is a Monteggia variant with an ulna bowing in which only the radial head dislocation is seen. Initially, clinical complaints are mild, but after years of lack of pressure in the joint between capitellum and the radial head, deformation of the radial head will occur. The articular surface becomes dome-shaped and the head circumference enlarges. At some stage, these dysplastic changes become irreversible, forming a contra-indication for corrective surgery. The risk of complications or re-dislocation of the radial head increases if radial head deformation progresses.

Current work-up to restore the posttraumatic anatomy by a corrective surgery includes a plain radiograph of the elbow, including the forearm. The head/neck ratio may be enlarged due to the widened circumference of the radial head[13, 14]. There is yet no cut-off value for the head/neck ratio that contraindicates surgery, and a large variance is present in healthy individuals. Therefore, the use of quantitative three-dimensional CT scans (Q3DCT) as a tool for objective assessment of radial head dysplasia was explored. The hypothesis was that Q3DCT might be valuable to determine the remaining concavity of the radial head articular surface, or as a tool for objective assessment of radial head enlargement (radial head volume)[15]. Display of relief in the articular surface in coloured areas that represent convex and concave areas may form a tool for the surgeon to estimate the amount of radial head concavity. Unfortunately, calculating the percentage of concave articular surface was unreliable. Also, there was no significant difference in radial head volume between missed Monteggia (MM) patients and age/sex-matched controls. There seemed to be a trend towards a larger radial head surface in MM, but potentially the number of ten cases was too low to enable adequate statistic evaluation. The head/neck ratio was enlarged in MM patients, and there was a significant correlation between Q3DCT radial head volume values and the head/neck ratio. It may be concluded that Q3DCT is, unfortunately, no reliable tool for improving the objective assessment of radial head dysplasia. Although optically, the heat maps that were obtained by Q3DCT may be of value, interpretation is highly subjective and, thus, less useful in determining the severity of radial head deformation.

Interestingly, in the case series of both papers in this part of the thesis, the preoperative estimation of head/neck ratio and radiologic dysplastic features did not correlate to intraoperative descriptions of the surgeon or the difficulty to reduce the radial head. In cases in which easy radial head reduction was possible, redislocation occurred and vice versa. This emphasises the need for a new tool that validates radial head and lesser sigmoid notch dysplastic features and aids in decision-making in the preoperative work-up. It also underlines that dysplastic features are just one of the many factors that contribute to difficult radial head reduction and redislocation risk in corrective surgery for MM. Pulling forces around the elbow (like IOM, biceps, pronator teres and supinator muscles) and radioulnar length discrepancy are examples of other factors that are of influence on radial head re-dislocation. This complies with previous studies that showed that multiple factors are of influence on radiocapitellar congruence following chronic radial head dislocation[15, 16].

All separate steps of surgical correction of a chronic radial head dislocation in MM may be subject to discussion, as pointed out in chapter seven.

Firstly, there is a discussion regarding the potential success of a closed reduction (CR) of the radial head. Some state that, in chronic MM, CR may be attempted, and open reduction (OR) is only necessary in those patients where closed reductions has failed[17]. However, there is a convincing amount of literature that describes that adequate reduction of the radial head may be blocked by the annular ligament that becomes entrapped within the joint[18, 19], or even may be buttonholed through the capsule or surrounding muscles[20]. In all cases from the series from our practice, dense scar tissue was found in the radiocapitellar joint. Therefore, an open debridement seems essential for adequate radial head reduction. Another advantage of OR is that OR also allows for a direct visual on the radial head while the ulna osteotomy is performed.

Corrective surgery for MM should then ideally restore forearm biomechanics by correcting ulna bowing and relative ulna shortening. It is a challenging procedure, that should be carried out exclusively by experienced surgeons with profound understanding of the complex biomechanics and surgical procedures of the elbow and forearm. Theoretically, using IOM pulling forces may enhance radial head reduction, so several publications advertise a slight ulna bending and elongating overcorrection to obtain an extra downward pull of the radial bone. In chapter seven, the literature is reviewed to provide an overview of known pearls and pitfalls for the surgical technique for MM correction. Knowledge regarding the most optimal (steps of the) procedure is still growing, and insights are constantly evolving as experience with this complex corrective surgery increases.

Finally, there is also still no consensus on the best fixation for corrective surgery following MM. Gradual lengthening and bending by external fixation is an option[21], which confines the child to a construction of pins and metal around the arm for several months. The advantage is that potential complications due to sudden lengthening may be prevented. Controlled plate fixation under a direct visual of the radiocapitellar joint allows for a more rigid fixation that enables movement from the first postoperative moment. In children, this seems a more tolerable fixation option.

The most crucial point of discussion regarding corrective surgery for MM is that, even after summing up all the literature on this topic, the decision to perform a corrective surgical procedure should be a thoroughly weighed decision for every individual patient and their parents. There is a high risk of complications that may be of great impact on a growing child. Opposite to that, there is a certain point of no return if dysplastic features reach an extent at which radial head reduction will undoubtedly be unsuccessful.

Future perspectives

There is still a challenge in predicting the presence of associated injuries in pRNF: traditional fracture classifications do mostly not include potential injury to surrounding bones or ligaments, and history taking and physical examination may be unreliable in children, as mentioned above. It may be good to realise that if medial pain or haematoma is present, more stringent follow-up may be indicated because of a higher chance of fracture redislocation in case of medial collateral ligament injury. MRI or stability tests (under general anaesthesia) may be considered. Ultrasound has not yet been explored as a potential alternative, but may be an interesting option too. Before these considerations are applied clinically, prospective research is needed and there should be more certainty regarding the influence of associated injuries on outcome.

Three-dimensional CT-scans, and even four-dimensional movement of the digitally reconstructed bones, are promising new techniques for assessing all aspects of radiocapitellar and PRUJ deformity. Potentially there is even a role for three-dimensional preoperative planning of the ulna osteotomy in MM, for example by an estimation of the optimal position of the osteotomy. In MM and pRNF, preoperative three-dimensional CT scanning with an option to compare to the contralateral side (MIMICS) may be a valuable tool that would be interesting to study in the context of these injuries. Occult fractures, joint space asymmetry, or ulna bowing may be identified by comparing to the unaffected side. In the case of MM, MIMICS may be very valuable in confirming a posttraumatic cause of the radial head dislocation, assessing radial head dysplasia and the amount of radioulnar length discrepancy and the status of the proximal radioulnar joint. Whether this technique may also be of value to perform preoperative planning should be studied thoroughly because several factors besides osseous features are of influence, like soft tissue pulling forces.

It would be interesting to include the effect of growth in future studies on all three topics of this thesis. Potentially, younger children experience a different injury mechanism due to the relatively soft cartilaginous tissue in the physes[22]. An illustrative detail is that the youngest child with an elbow dislocation in chapter four was seven years old. That said, the diagnosis in very young children is simply more difficult due to their general flexibility. Potentially, bias applies because elbow dislocation injuries are more frequently missed in very young children. Around 25 percent of radial length growth is provided by the proximal physis. The remodelling potential for malaligned fractures may be higher in young children. It is therefore possible that the choice of treatment should differ for children under a certain age; the same goes for corrective surgery for MM. Future research could include the exploration of growth models for prediction of the effect of growth.

Conclusions and clinical implications

Radial neck fractures and Monteggia injuries may be unforgiving injuries in children. Late sequelae may arise if associated injuries are missed in pRNF, or if the Monteggia injury is not recognised. One third of pRNF has associated injuries, regardless of patient age or fracture angulation. How these injuries affect the outcome of treatment remains uncertain. In theory, a specific group of patients may benefit from intensified follow-up. Remodelling potential is limited in the proximal radius, and dysplastic changes to the radiocapitellar and PRUJ may occur. Corrective surgery following both types of injuries is technically challenging, with a high risk of complications. By depicting potential safe zones with new techniques like CASAM, injury to small cutaneous nerves may be prevented. In corrective surgery following MM, restoration of elbow and forearm biomechanics is key. This may best be obtained by an open radiocapitellar and PRUJ debridement, followed by an ulna osteotomy with a slight overcorrection to tension the IOM.

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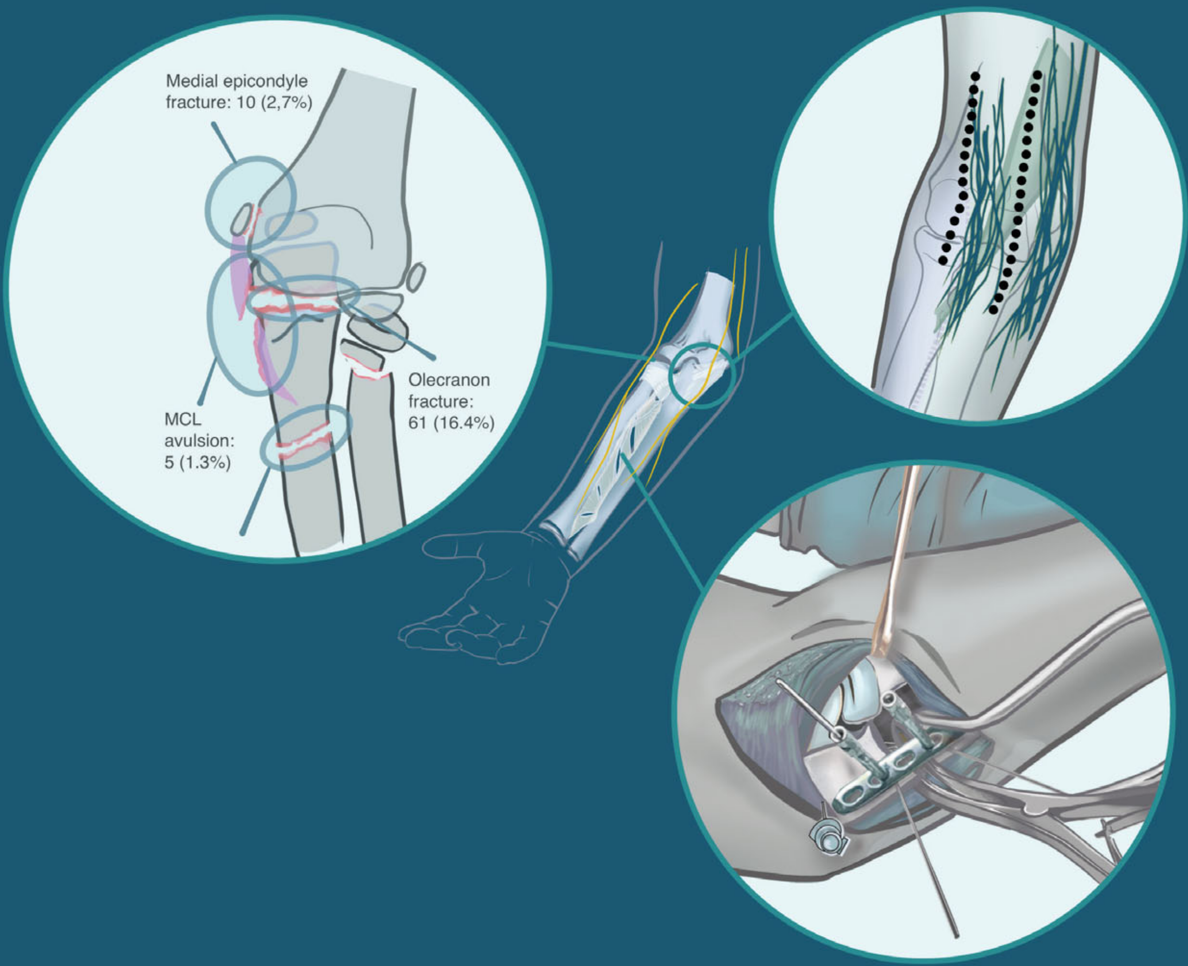
Medial epicondyle
fracture: 10 (2,7%)
Olecranon
fracture:
61 (16.4%)
MCL
avulsion:
5 (1.3%)

CHAPTER 10

Clinical implications and take-home messages

1. If traditional anterior elbow incisions like the Henry approach or the Boyd Anderson approach are shifted slightly into the most lateral quadrant of the elbow or the 2/4 medial quadrant, seen in the coronal plane, injury to cutaneous nerves may be avoided.
2. Surgeons should be aware that there is no “safe zone” for surgery to the medial elbow; a medial antebrachial cutaneous nerve branch will always be encountered. Careful dissection is advised and surgical field magnification through loupe glasses may be considered.
3. Knowledge of the biomechanics of injury is eminent in the treatment of pediatric elbow injury.
4. Deduction of the trauma mechanism in pRNF may be more reliable in estimating the severity of the injury than fracture angulation. Current fracture classifications are underestimating surrounding injuries.
5. 1/3 of pediatric radial neck fractures include associated injury, like (occult) fractures or ligamentous injuries, regardless of patient age or fracture angulation. More research is needed to gain knowledge on the impact of these associated injuries on treatment outcome. A more stringent follow-up to identify elbow instability or fracture re-displacement at an early stage may be considered to prevent late sequelae.
6. Corrective surgery for chronic radial head dislocation in a missed Monteggia lesion should ideally restore forearm biomechanics. An open debridement of the radioulnar and radiocapitellar joint is key. The ulna osteotomy should be lengthened and angulated to restore radioulnar length discrepancy and enhance the downward pulling forces of the interosseous membrane.

APPENDICES

A

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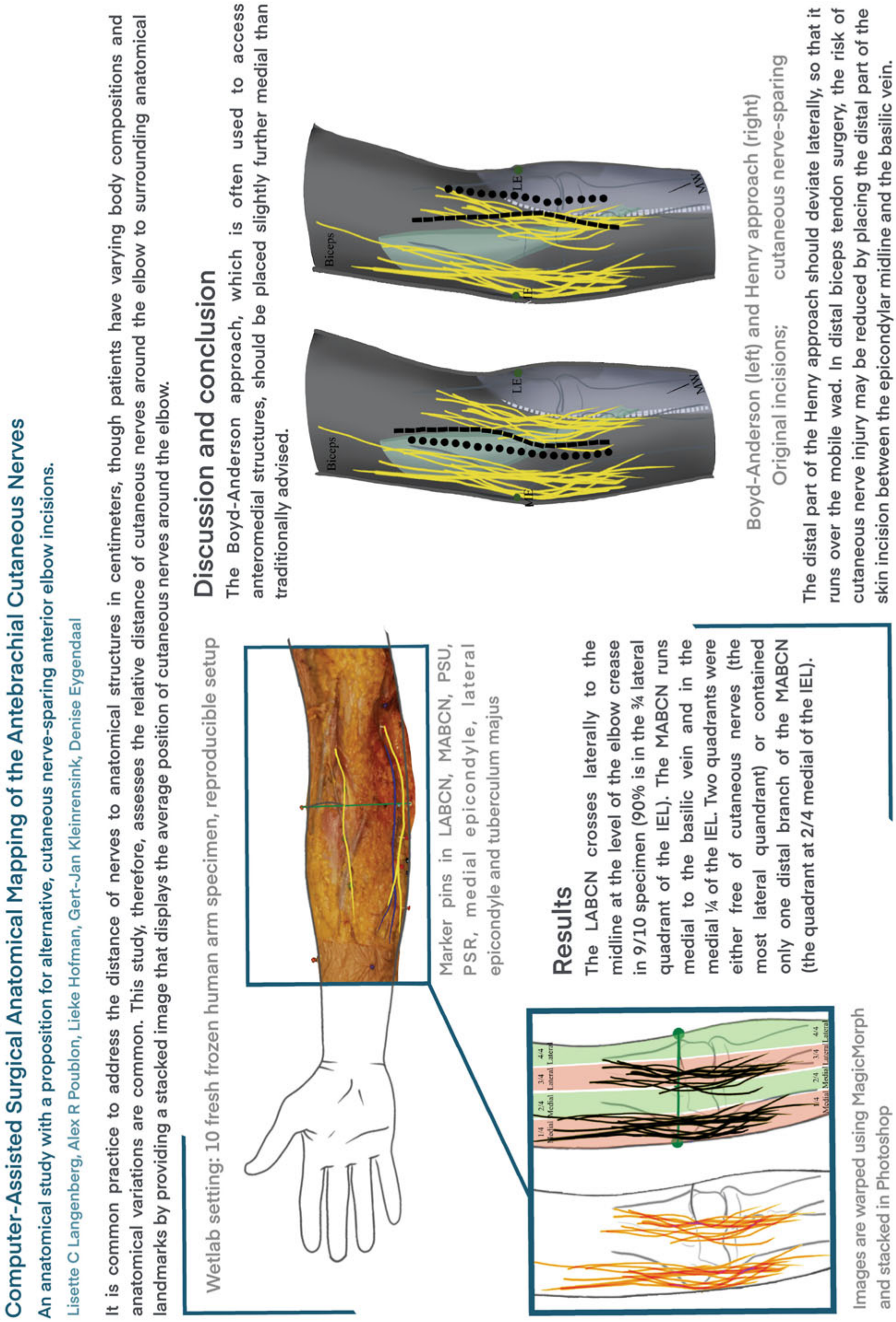

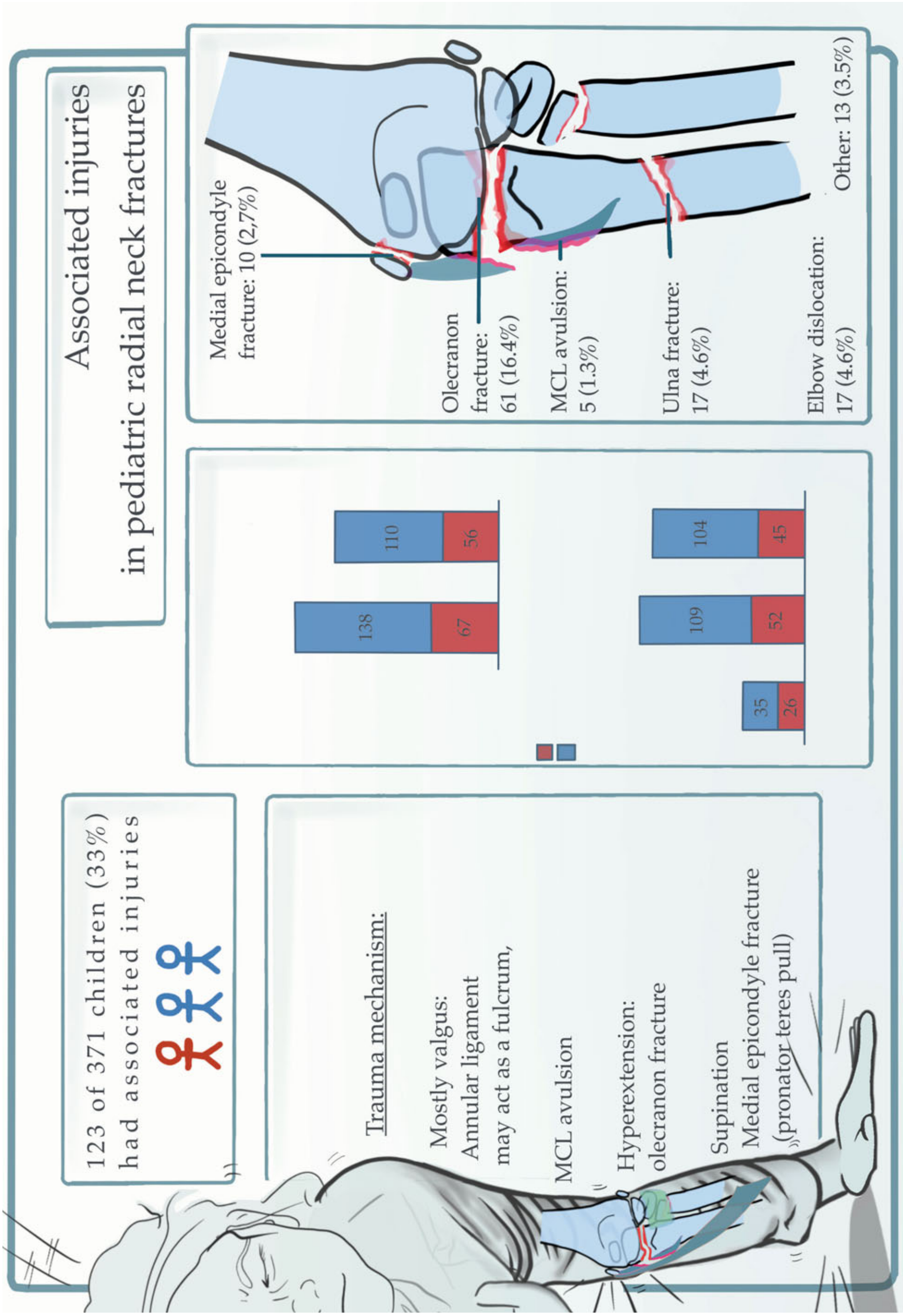

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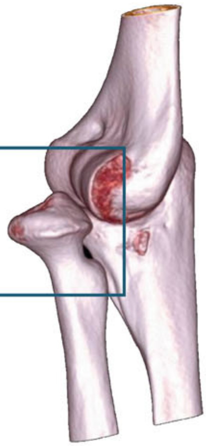
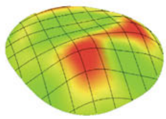
Radial Head Volume Measurements using Quantitative Three Dimensional CT images for Radial Head Deformation following missed Monteggia lesions

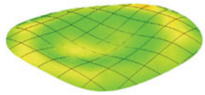
Lisette C.Langenberg; Stein J.Janssen; Denise Eygendaal

In chronic radial head dislocation, the radial head may enlarge and become dome-shaped. To date there is no validated tool to quantify radial head deformation and predict its influence on surgical outcome.



Quantitative three-dimensional CT-scan (Q3DCT) analysis

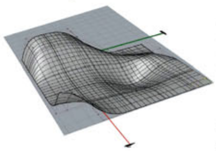




10 Missed Monteggia

10 Age/sex matched controls

Surface area calculations using Rhino



	10 Missed Monteggia	10 Age/sex matched controls	
Radial head volume	1487 mm3	1163 mm3	p=0.32
Articular surface size	282 mm3	236 mm3	p=0.33

Results

The radial head volume and radial articular surface size did not differ significantly between patients with missed Monteggia lesions and age/sex matched controls. Optically, heat maps of the articular surface of missed Monteggia patients did not differ notably from control heat maps. A higher head/neck ratio correlated to a larger radial head volume (Pearson r=0,73; p=0,02).

Discussion and conclusion

Q3DCT may be an interesting tool in the preoperative workup of pediatric missed Monteggia lesions. Prospective research with larger cohort sizes and data that compares the affected side to the contralateral elbow is needed to assess its true clinical potential.

Link to article: https://www.sciencedirect.com/science/article/pii/S2666638322002286

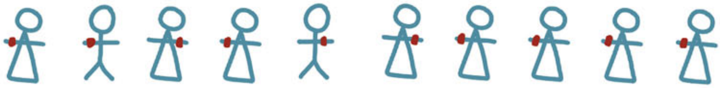
Surgical treatment of chronic anterior radial head dislocations in missed Monteggia lesions in children: A rationale for treatment and pearls and pitfalls of surgery

Langenberg LC, Beumer A, The B, Koenraadt K, Eygendaal D.
Shoulder Elbow. 2020 Dec;12(6):422-431.

The treatment of chronic radial head dislocations after Monteggia lesions in children can be challenging. This article provides a detailed description and clinical evaluation in 10 patients of the most frequently performed surgical technique: an ulna osteotomy followed by annular ligament reconstruction.

Preoperative, directly postoperative and 1 year postoperative X-ray

Inclusion: All paediatric patients 2008 - 2014



Age at surgery	8.8	12.6	7.6	6,1	5.3	6.3	9.8	9.4	7.8	13.2
Injury-surgery interval	4y	1y	2y	1.5m	1y	3y	2y	2y	unknown	2y
Δ Flexion 13.9	25	20	-10	35	-10	0	-5	45	0	20
Δ Extension 4.2	10	-7	-20	30	10	0	5	0	5	10
Δ Pronation 4.3		5	0	25		0		10	0	-10
Δ Supination 20.0	15	0	15	60		0		40	0	30

Results

10 patients, with a mean follow-up of 2.5 years. Postoperative range of motion generally improved 30.7°. Even in a patient with obvious deformity of the radial head, range of motion improved after surgery, without residual dislocation of the radial head.

Discussion and conclusion

Corrective proximal ulna osteotomy with rigid plate fixation and annular ligament reconstruction yields good results in patients with chronic radial head dislocation following a Monteggia lesion. Surgery should be considered regardless of patient age or time since trauma. Given substantial arguments in literature, we discourage surgery if a CT scan shows dome-shaped radial head dysmorphic features in work-up to surgery.

Link to article: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7689610/

Appendix II: Dutch summary / Nederlandse samenvatting

Samenvatting

Hoofdstuk één is een algemene inleiding tot dit proefschrift, waarin de relevante anatomie, biomechanica en veelvoorkomende letselpatronen van de (kinder)elleboog worden uitgelegd. De mogelijke effecten van groei worden besproken en de pathofysiologie van posttraumatische deformatie en aanhoudend functieverlies bij kinderen wordt toegelicht.

Deel één: gedetailleerde evaluatie van anatomische variaties van de huidzenuwen rond de elleboog met behulp van Computer Assisted Surgical Anatomy Mapping (CASAM).

Het eerste deel van dit proefschrift omvat een nauwgezette studie van de cutane zenuwtakken rond de elleboog. Het sparen van deze delicate zenuwen is van het grootste belang om pijnlijke neuromen of een veranderde sensibiliteit van de huid rond elleboog of onderarm te voorkomen.

De sensibiliteit van het laterale deel van de onderarm wordt verzorgd door de laterale antebrachiale cutane zenuw (LABCN). Deze verloopt onder de laterale rand van de biceps vandaan naar de onderarm, en wordt gevormd wordt door een tak van de nervus musculocutaneus. De mediale antebrachiale cutane zenuw (MABCN) zorgt voor de sensibiliteit van het mediale deel van de onderarm en loopt grotendeels nabij en parallel aan de vena basilica ter hoogte van de elleboogplooi, ofwel de interepicondylaire lijn. Beide zenuwen hebben een grote variatie in hun verloop en aantal vertakkingen tussen individuen. De weergave van kleine cutane zenuwen in anatomieboeken is slechts één mogelijke optie voor het verloop van deze zenuwen. Idealiter zouden chirurgen hun incisies moeten kunnen plannen in een “safe zone”, die zo min mogelijk cutane zenuwvertakkingen bevat. CASAM is een techniek die nuttig is gebleken bij het weergeven van kleine zenuwen van verschillende preparaten in één samenvattende gestapelde afbeelding. In een anatomisch laboratorium wordt een raster gecreëerd waarin anatomische herkenningspunten worden gemarkeerd. Het verloop van interessante structuren, in dit geval cutane zenuwtakken, kunnen met pinnen worden gemarkeerd. Vervolgens worden individuele afbeeldingen bewerkt met behulp van MagicMorph-software, die rekening houdt met de relatieve afstand van anatomische structuren en driedimensionale verhoudingen van weefsel. In **hoofdstuk twee** wordt het verloop van de MABCN beoordeeld in tien menselijke preparaten met behulp van CASAM. Letsel aan deze zenuw is gerapporteerd na chirurgische ingrepen aan de mediale zijde van de elleboog, elleboogartroscopie en zelfs na kleine ingrepen zoals venapuncties. De incidentie van MABCN-letsel na een operatie wordt mogelijk onderschat, omdat het geen item is in de meeste door patiënten gerapporteerde uitkomstschalen. Hoewel de symptomen mild en zelflimiterend kunnen zijn, worden voorbeelden beschreven van invaliderende pijn als gevolg van neuromen of een beperking van de bewegingsuitslag van de elleboog. Een groot deel van de patiënten die aanhoudende pijn ervaart na een operatie aan de nervus ulnaris, kan in feite MABCN-geïnduceerde klachten hebben. Het doel van deze studie was om te beoordelen of er een “safe zone” is aan de mediale zijde van het ellebooggewricht die geen takken van de MABCN bevat.

In hoofdstuk 2 wordt beschreven hoe alle MABCN-takken rond de mediale elleboog zijn vrijgeprepareerd en gemarkeerd in tien menselijke preparaten. Met behulp van CASAM werd het gemiddelde verloop van de mediale antebrachiale cutane zenuw (MABCN) in beeld gebracht. In 90 graden flexie was er een grote variatie in het verloop van de MABCN, zonder een duidelijk gedefinieerde veilige zone voor chirurgische benaderingen. Een belangrijke conclusie is dat chirurgen zich bewust zouden moeten zijn van het feit dat er altijd cutane zenuwtakken door het operatiegebied lopen tijdens mediale ingrepen rond de elleboog. Mediale huidincisie moeten bedachtzaam worden uitgevoerd om geen schade te veroorzaken aan MABCN-takken.

Zowel de LABCN als de MABCN worden in **hoofdstuk drie** afgebeeld met behulp van CASAM. Traditionele anterieure huidincisies rond de elleboog, zoals de Boyd-Anderson en Henry-benadering, maken gebruik van anatomische herkenningspunten zonder rekening te houden met het verloop van de onderliggende huidzenuwen. Ze zijn gebaseerd op het “internervous plane”; het vlak dat tussen vaten en zenuwen toegang biedt tot diepere structuren. De LABCN loopt ook risico bij de chirurgische benadering van de distale bicepspees. In hoofdstuk drie werden tien preparaten van de menselijke arm gebruikt om de meest voorkomende huidzenuwen rond de elleboogplooi te identificeren. Het doel was om een zone te identificeren met een minimaal risico op huidzenuwletsel (“safe zone”). Een van de belangrijkste conclusies was dat het meest laterale kwadrant grotendeels vrij was van huidzenuwen. Indien de Henry-benadering licht lateraal zou afwijken zodat de incisie in het meest laterale kwadrant van de elleboog loopt, kan daarom letsel aan takken van de LABCN worden voorkomen. De Boyd-Anderson-benadering kan iets verder mediaal worden geplaatst, maar in het disale deel van de incisie, lateraal ten opzichte van de vena basilica. Dit plaatst de nieuwe huidincisie in de 2/4 mediale zone, die geen huidzenuwen bevat. Beide incisies dienen alleen in hun oppervlakkige verloop te worden aangepast; diepere structuren kunnen het beste in hun *internervous plane* worden benaderd, zoals traditioneel wordt geadviseerd.

Deel twee: Uitkomst van elleboogtrauma bij kinderen

Radiushalsfracturen kunnen geisoleerd optreden, of onderdeel zijn van een groter letsel, waarbij meerdere structuren betrokken zijn; zogenaamde *geassocieerde letsels.* **Hoofdstuk vier** gaat dieper in op de incidentie van geassocieerde letsels bij radiushalsfracturen in kinderen (pRNF). Er is weinig bekend over de aard van deze letsels en de impact die de aanwezigheid ervan zou moeten hebben op therapiekeuze en nabehandeling. Er wordt aangenomen dat er bij kinderen ouder dan tien jaar andere geassocieerde letsels voorkomen dan bij kinderen jonger dan tien jaar, vanwege de verharding van de groeischijven met progressie van de groei. Verschillende auteurs van eerdere literatuur over dit onderwerp stellen ook dat een toegenomen angulatie van de radiushals een meer hoogenergetisch letsel vertegenwoordigt. Mogelijk is er een correlatie met de mate van angulatie van de radiushals en de kans op aanwezigheid van geassocieerd letsel. Hoofdstuk vier bevat een meta-analyse van 371 individuele pediatrische casussen van pRNF. Het doel was om te evalueren hoe de incidentie is van geassocieerde letsels, zoals ulnafracturen, ligamentletsel of elleboogluxaties. Er waren 123 kinderen met geassocieerde letsels (33,2%). Een meta-analyse van onze gegevens toonde aan dat de incidentie van geassocieerde letsels niet gecorreleerd is met leeftijd of Judet-classificatie (mate van fractuurangulatie). Olecranonfracturen en ulnafracturen kwamen het vaakst voor. Chirurgen kunnen een betere indruk krijgen van de ernst van het elleboogletsel en de betrokken structuren door het traumamechanisme af te leiden, dan door traditionele classificaties zoals Mason, Judet of O'Brien te gebruiken, die uitsluitend gebaseerd zijn op radiografische criteria.

Tot nu toe is er min of meer consensus in de literatuur dat er een behandeling (repositie met of zonder fractuurfixatie) noodzakelijk is wanneer een radiushalsfractuur meer dan 30 graden geanguleerd staat (Judet-types 3 en 4). Het is nog niet bekend welke behandeling de voorkeur heeft. In **hoofdstuk vijf** was het doel te beoordelen of specifieke groepen kinderen met radiushalsfracturen (pRNF) baat zouden hebben bij een bepaalde chirurgische behandeling. Na een PRISMA-guided systematische review werden gegevens over de Judet-classificatie, het type behandeling, de follow-upduur en de bewegingsuitslag geëxtraheerd uit eerder gepubliceerde case series. De behandelingsmethoden omvatten open of gesloten repositie (OR of CR), Kirschner-draadfixatie (Kw) of gesloten intramedullaire pinfixatie (CIMP). De resultaten impliceren dat er een licht voordeel is van Kw in de 30-60 graden (Judet 3) groep ten opzichte van CIMP-fixatie, wat betreft de bewegingsuitslag bij follow-up (Kw 9,7% verminderd versus CIMP 32,6% verminderd, p = 0,01). Bovendien trad in meer dan 50% van de gevallen die een open repositie (OR) vereisten, een verlies van bewegingsuitslag op.

Deel drie: gemiste Monteggia-letsels

Monteggia-letsels zijn complexe en vaak gemiste letsels, die bestaan uit een combinatie van een ulnafractuur en een dislocatie van de radiuskop. In eerste instantie veroorzaakt de radiuskopluxatie geen symptomen, omdat rotaties in geluxeerde stand vaak vrij mogelijk zijn. Na verloop van tijd vervormt de radiuskop echter door een gebrek aan druk op het gewrichtsoppervlak, wat klachten kan veroorzaken zoals verminderde bewegingsuitslag (met name flexie), neurologische klachten, valgusafwijking van het elleboogggewricht en pijn rond de radiuskop als gevolg van impingement (inklemming) van omliggende anatomische structuren. Patienten met gemist Monteggia letsel presenteren zich daarom vaak maanden tot jaren na het oorspronkelijke letsel, met een chronische radiuskopluxatie.

In **hoofdstuk zes** wordt de work-up voor een operatieve correctie voor gemiste Monteggia-letsels geëvalueerd. Daarnaast is onderzocht of metingen middels Quantitative three-dimensional CTscans (Q3DCT) een betrouwbaardere tool zijn voor het inschatten van deformatie van de radiuskop dan huidige gebruikte technieken. Radiuskopdeformatie bij gemiste Monteggia omvat meestal verbreding van de omtrek van de radiuskop en uitstulping van het gewrichtsoppervlak, dat bol wordt, ofwel *dome-shaped*. Als deze dysmorfe kenmerken zo uitgebreid worden dat het radiocapitellaire gewricht niet meer congruent kan worden, is correctieve chirurgie gecontra-indiceerd. Tot op heden is er nog geen betrouwbaar instrument voor preoperatieve inschatting van de mate van radiuskopdeformatie. In hoofdstuk zes was de hypothese dat exacte berekeningen van radiuskopkenmerken met behulp van oppervlaktemetingen middels Q3DCT een nuttige, objectieve tool zouden kunnen zijn bij het beoordelen van de deformiteit van de radiuskop. Er waren echter geen statistische verschillen in de grootte van het gewrichtsoppervlak of het percentage concaaf gewrichtsoppervlak tussen tien kinderen met chronisch gemiste Monteggia en leeftijds-/geslachtsgematchte controle patienten.

Q3DCT maakt het ook mogelijk om het reliëf van het gewrichtsoppervlak in een heatmap weer te geven. Deze heatmaps kunnen wel waardevol zijn omdat ze de chirurg een gedetailleerd beeld geven van het gewrichtsoppervlak. De interpretatie van deze beelden is echter subjectief.

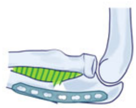
Wanneer besloten wordt tot operatieve correctieve van gemiste Monteggia-laesies kan de operateur kiezen uit een reeks stappen: open of gesloten repositie (OR of CR) van de radiuskop, ulna-osteotomie (UO) en reconstructie van het annulare ligament (ALR). Het is nog steeds onzeker of al deze stappen noodzakelijk zijn voor een succesvolle radiuskoprepositie. Sommigen beweren dat UO alleen moet worden uitgevoerd als er duidelijke tekenen van angulatie of bowing in de ulna zijn, of als er nog steeds instabiliteit is na ALR. De meeste auteurs stellen echter dat UO essentieel is en dat zelfs overcorrectie noodzakelijk is om redislocatie van de radiuskop te voorkomen.

In **hoofdstuk zeven** wordt een systematische literatuur search uitgevoerd, waarbij alle case series met daarin kinderen met gemist Monteggia letsel worden geincludeerd. Details over de chirurgische technieken werden geëvalueerd, en pearls en pitfalls worden gepresenteerd. Ervaringen uit de kliniek worden gepresenteerd aan de hand van de data van tien patiënten. Een van de conclusies is dat chirurgische correctie van een chronische radiuskopluxatie na gemist Monteggia letsel een uitdagende ingreep is, waarbij uitgebreide achtergrondkennis en ervaring ten aanzien van de anatomische biomechanica van elleboog en onderarm essentieel zijn.

Appendix III: List of abbreviations

AL	Annular ligament (part of LCLC)
ALR	Annular ligament reconstruction
AMCL	Anterior Medial Collateral Ligament (elbow, part of MCLC)
CASAM	Computer-assisted surgical anatomical mapping
CB	Central band (ligament in IOM)
CIMP	Closed Intramedullary pinning (elbow / forearm), may also be referred to as Metaizeau technique
CR	Closed reduction
CT	Computional Tomography (CT-scan)
DOB	Distal oblique band (ligament in IOM)
DRU / DRUJ	Distal radioulnar joint (wrist, joint between distal radius and ulna)
F/E	Flexion / Extension
IELI	nter epicondylar line (elbow, line between medial and lateral epicondyle)
IOM	Interosseous membrane (forearm, membrane between ulna and radius)
IPD	Individual patient data
KLADILADI	Klap Die Laptop Dicht
Kw	Kirschner Wire, may also be referred to as ‘pinning’.
LABCN	Lateral antebrachial cutaneous nerve
LCLC	Lateral Collateral Ligament Complex (elbow, includes RCL, AL, LUCL)
LE	Lateral epicondyle (elbow)
LUCL	Lateral Ulnar Collateral ligament (part of LCLC of the elbow)
MABCN	Medial Antebrachial Cutaneous nerve
MCLC	Medial collateral ligament complex (elbow, includes AMCL, TMCL and PMCL)
ME	Medial epicondyle (elbow)
ORO	pen reduction
PIN	Posterior interosseous nerve (elbow/forearm)
PMCL	Posterior medial collateral ligament (elbow, part of MCLC)
P/S	Pronation / Supination
pRNF	pediatric radial neck fracture (RNF)
PRU / PRUJ	Proximal radioulnar joint (elbow, joint between proximal radius and ulna)
PSR	Processus Styloideus Radialis (wrist, radial styloid)
PSU	Processus Styloideus Ulnae (wrist, ulnar styloid)

Q3DCT	Quantitative 3-Dimensional CT
RCL	Radial Collateral ligament (elbow, part of LCLC)
RHD	Radial head dislocation (in this thesis: part of Monteggia lesion)
ROM	Range of Motion
RNFR	adial neck fracture
RSNR	adial superficial nerve
TM	Tuberculum minus (shoulder, anatomical landmark on proximal humerus)
TMCL	Transverse Medial Collateral Ligament (elbow, part of MCLC)
UCL	Ulnar Collateral Ligament (in this thesis: elbow, part of LCLC, = LUCL)



Appendix IV: PhD Portfolio

Summary of PhD training and teaching

		Year	Workload (Hours/ECTS)
General courses			**2.6**
-	Research Integrity	2024	0.3
-	WMO-GCP	2023	0.3
-	Evidence Based Chirurgie	2017	1
-	Basiscursus SPSS *Linnaeusinstituut, Haarlem*	2013	1
Specific courses (e.g. Research school, Medical Training)			**13.4**
-	*Advanced Trauma Life Support (ATLS)*	*2011*	*2*
-	*Fundamental Critical Care Support (FCCS)*	*2012*	*2*
-	*Advanced Wilderness Life Support (AWLS)*	*2013*	*2*
-	Edinburgh Trauma Course	2016	1.5
-	OTC 1: “the basics”	2017	0.5
-	OTC 2: gesloten fractuurbehandeling	2017	0.5
-	OTC 3: “more than basic”	2018	0.5
-	Basiscursus arthroscopie	2018	0.5
-	UMCU elbow arthroscopy	2018	1
-	Dissection course elbow/wrist VuMC	2020	0.5
-	Amsterdam Skills Center lower arm/wrist anatomy	2021	0.5
-	Communicatiecursus Q-Academy	2021	0.3
-	Stralingsbescherming voor medisch specialisten	2022	1
-	Patient Journey, MOOC (online course) *TU Delft*	2023	0.6
Seminars and workshops			**2.4**
-	FESSH degenerative hand disease 3x online webinar	2021	0.5
-	Esser Course CMC1	2013	1
-	Multiple online webinars (FESSH, Beemed, Global Elbow Network)	2021-2025	0.3
-	2nd Mediterranean symposium, on elbow instability, *Marseille, France,* 2-day event	2024	0.6
Presentations			**8.3**
-	**Presentation:** Langenberg LC, optimizing transmural and patient communication in treatment of subacromial shoulder complaints, *Jaarcongres Schoudernetwerk Nederland, den Bosch, december 2023*	2023	0.5
-	**Presentation:** Langenberg LC, van den Ende KIM, Reijman M, Boersen GJJ, Colaris JW. *Annual meeting of the International Orthopaedic Trauma Association, dec 2022, Amsterdam*	2022	0.5
-	**Presentation:** Lisette C Langenberg, Paolo Arrigoni, Beemed Webinar: Computer Assisted Surgical Anatomical Mapping of the cutaneous nerves around the elbow. *17 nov 2022, online webinar.*	2022	0.5

	Year	Workload (Hours/ECTS)
- **Presentation:** Lisette C Langenberg, Stein J Jansen, Denise Eygendaal: Quantitative three dimensional CT analysis for radial head deformation following Monteggia lesion. *ESSKA conference, april 2022, Paris*	2022	0.5
- **Presentation:** Langenberg LC, Poublon AR, Hofman L, Klein-Rensink GJ, Eygendaal D. Introducing a new anteromedial portal for elbow arthroscopy: Nerve-sparing portal placement cased on CASAM. *ESSKA conference, april 2022, Paris*	2022	0.5
- **Poster:** Langenberg LC, Vieira Lima G, Heitkamp SE, Kemps FLAM, Jones MS, Moreira MAAG, Eygendaal D. The surfer's Shoulder. *ESSKA conference may 2021, online.*	2021	0.5
- **Presentation:** Lisette C Langenberg, Sebastiaan E Heitkamp, SMI webinar series: the surfers' shoulder. *online Webinar.*	2021	0.5
- **Presentation:** De Surfers schouder, chronische schouderklachten door golfsurfen. *Sportmedisch wetenschappelijk jaarcongres, nov 2019, Almelo, Nederland*	2019	0.5
- **Poster:** Langenberg LC, Beumer A, The B, Koenraadt K, Eygendaal D; "Surgical treatment of chronic anterior radial head dislocations in missed Monteggia lesions in children; a rationale for treatment and pearls and pitfalls of surgery". *Amphia wetenschapsdag, nov 2018*	2018	0.5
- **Poster:** Kemps FLAM, Langenberg LC, Incidence of surf induced shoulder complaints in physiotherapy practices in the Netherlands. *Annual conference, Surfing Medicine International, Cornwall, sep 2018. Awarded second prize for best poster presentation.*	2018	0.5
- **Presentation:** Langenberg LC, Langeveld A: Surf Blessures, *Boerhaave nascholing voor huisartsen, LUMC, 31 mei 2018.*	2018	1
- **Presentation:** Langenberg LC, Kemps FLAM: Schouderklachten bij golfsurfers. *nov 2017, HMC symposium Regionaal Schoudernetwerk.*	2017	0.5
- **Presentation:** Langenberg LC, Beumer A, The B, Koenraadt K, Eygendaal D; "Pearls and Pitfalls of surgery for Missed Bado 1 Monteggia lesions". *Trauma Platform Symposium, aug 2016.*	2016	0.5
- **Presentation:** Surf&Science. European association of surfing doctors Students symposium, Erasmus MC Rotterdam	2015	0.5
- **Publicatie op congres, presentation door collega:** Aleid Ruijs, Joel Rezzouk, Lisette Langenberg, Hand trauma while surfing: A case series and analysis of fracture patterns Congrès annuel de la Société francaise de chirurgie de la main / Chirurgie de la main 34 (2015) 332-398	2015	0.3
- **Poster**: Langenberg LC, Dumont EAWJ, Transverse fracture of the distal phalanx following surf leash injury, a case report and review of the literature Third annual conference, European Association of Surfing Doctors, september 9th-13th, Sligo, Ireland.	2014	0.5
(Inter)national conferences / Conference organisation		**2**
- Annual International Conference Organisation for Surfing medicine International (SMI)	2014, 2015	1 1

2. Teaching

		Year	Workload (Hours/ECTS)
Lecturing			**7.6**
-	Guest lecturer, Kinderorthopedie, huisartsopleiding UMCU	2018-2021	3
-	KTO Onderwijs co-assistenten NWZ	2020-202	0.5
-	Lecturer, medical sciences (opleiding geneeskunde), Erasmus MC	2024	0.5
	Wetlab anatomy of the upper extremity course, first year students (Snijzaal bovenste extremiteit)	2025	0.5
	Colleges elleboog, onderarm en reumatologie	2025	1
-	Faculty Esser course		
	"Essential rotation", wetlab presentation lateral elbow approaches	2024	0.5
	"Essential motion", wetlab presentation Thompson approach and workshop elbow physical examination	2025	1.0
	"Advanced fractures"	2025	0.3
-	Faculty LISA hand en pols (AIOS onderwijs)	2026	0.3
Supervising Master's theses			**3**
-	L Hofman, UMCU	2020	1
-	M. van den Boogaard, AMC	2021	2
Other			**6.0**
-	Workshop Surfers shoulder at annual conference SMI	2023	1.5
-	Development of patient information app, *patient journey*	2021-2023	3
-	Editing pocket "Acute Medicine", *Compendium Medicine* Role: text editing in team of supervising medical specialists	2025	1.5
-	Medical illustrator (www.medschets.nl)		
	- SECEC webinar marketing, *custom shoulder and elbow illustrations*		
	- Nederlands tijdschrift voor Reumatologie, *cover illustrator*,		
	- EMpact, *medical illustrator*		
	- Several individual scientific publications, phd covers and custom illustrations (www.medschets.nl/sfeerimpressie-en-publicaties).		

Appendix V: List of publications

List of publications

Published papers, PhD

Langenberg LC, Benner JL, Bernal Bader N, van Bergen CJA, Colaris JW. The Presence of Associated Injuries in Pediatric Radial Neck Fractures: A Systematic Review of the Literature and Meta-Analysis of Pooled Individual Patient Data. Children (Basel). 2025 Feb 27;12(3):300. doi: 10.3390/children12030300. PMID: 40150584; PMCID: PMC11941324.

Langenberg LC, Poublon AR, Hofman L, Kleinrensink GJ, Eygendaal D. Computer-Assisted Surgical Anatomical Mapping of the Antebrachial Cutaneous Nerves: An Anatomical Study with a Proposition for Alternative, Cutaneous Nerve-Sparing Anterior Elbow Incisions. JB JS Open Access. 2023 May 15;8(2):e22.00048. doi: 10.2106/JBJS.OA.22.00048. PMID: 37197699; PMCID: PMC10184984.

Langenberg LC, Janssen SJ, Eygendaal D. Radial head volume measurements using quantitative three-dimensional computed tomography images for radial head deformation following missed Monteggia lesions. JSES Int. 2022 Nov 22;7(6):2612-2616. doi: 10.1016/j.jseint.2022.10.011. PMID: 37969504; PMCID: PMC10638549.

Langenberg LC, van den Ende KIM, Reijman M, Boersen GJJ, Colaris JW. Pediatric Radial Neck Fractures: A Systematic Review Regarding the Influence of Fracture Treatment on Elbow Function. Children (Basel). 2022 Jul 14;9(7):1049. doi: 10.3390/children9071049. PMID: 35884033; PMCID: PMC9324597.

Langenberg LC, Beumer A, The B, Koenraadt K, Eygendaal D. Surgical treatment of chronic anterior radial head dislocations in missed Monteggia lesions in children: A rationale for treatment and pearls and pitfalls of surgery. Shoulder Elbow. 2020 Dec;12(6):422-431. doi: 10.1177/1758573219839225.

Langenberg LC, Eygendaal D, Corrective surgery for chronic anterior Monteggia dislocation. A review of the literature and workup to surgery. IBRA flash 2020, p19-21. Available at https://www.ibra.net/flash

Published papers, other

Van Den Boogaard M, **Langenberg LC**, The B, Van Bergen CJA, Eygendaal D. Preoperative Three-Dimensional Planning of Screw Length is not Reliable in Osteotomies of the Humerus and Forearm. Arch Bone Jt Surg. 2024;12(8):567-573. doi: 10.22038/ABJS.2024.72837.3611. PMID: 39211570; PMCID: PMC11353150.

Windt AEV, **Langenberg LC**, Colaris JW, Eygendaal D. Which radial head fractures are best treated surgically? EFORT Open Rev. 2024 May 10;9(5):413-421. doi: 10.1530/EOR-24-0035. PMID: 38726982; PMCID: PMC11099579.

Kraal T, Struijs PA, **Langenberg LC**, van Bergen CJ. Fractures around the shoulder in the skeletally immature: A scoping review. World J Orthop. 2023 Aug 18;14(8):604-611. doi: 10.5312/wjo.v14.i8.604. PMID: 37662664; PMCID: PMC10473910.

Langenberg LC, Botman M. Abandoning functional fixedness: Creative Solutions in Fracture Surgery Using Widely Available Materials. In: AIJR Proceedings; Proceedings of the 14Th European Conference on Creativity in Innovation (ECCI 2022). ISSN: 2582-3922; ISBN: 978-81-965621-1-3. DOI: https://doi.org/10.21467/proceedings.154.7

Langenberg LC, Vieira Lima G, Heitkamp SE, Kemps FLAM, Jones MS, Moreira MAAG, Eygendaal D. The Surfer's Shoulder: A Systematic Review of Current Literature and Potential Pathophysiological Explanations of Chronic Shoulder Complaints in Wave Surfers. Sports Med Open. 2021 Jan 6;7(1):2. doi: 10.1186/s40798-020-00289-0. PMID: 33409808; PMCID: PMC7788157.

Ruijs AC, **Langenberg LC**, Rezzouk J. Finger Trauma Due to Surfing; A Case Series and Analysis of Fracture Patterns. J Hand Surg Asian Pac Vol. 2017 Mar;22(1):10-13. doi: 10.1142/S0218810417500010. PMID: 28205479.

Todorov TI, de Bakker E, Smith D, **Langenberg LC**, Murakata LA, Kramer MHH, Centeno JA, Nanayakkara PWB. A Case of Silicone and Sarcoid Granulomas in a Patient with "Highly Cohesive" Silicone Breast Implants: A Histopathologic and Laser Raman Microprobe Analysis. Int J Environ Res Public Health. 2021 Apr 24;18(9):4526.

Hop MJ, **Langenberg LC**, Hiddingh J, Stekelenburg CM, van der Wal MB, Hoogewerf CJ, van Koppen ML, Polinder S, van Zuijlen PP, van Baar ME, Middelkoop E. Reconstructive surgery after burns: a 10-year follow-up study. Burns. 2014 Dec;40(8):1544-51. doi: 10.1016/j.burns.2014.04.014

Langenberg LC, Tebbes M, de Leeuw B. Een 85-jarige vrouw met een kyfose en dyspneu [An 85-year-old woman with an kyphosis and dyspnea]. Ned Tijdschr Geneeskd. 2012;156(25):A3308. Dutch. PMID: 22748364.

Langenberg LC, van Zuijlen PPM; “Marjolin’s ulcus, een maligniteit die zich voordoet als granulatieweefsel” Huisarts en Wetenschap, June 2015, Volume 58, Issue 6, p 340.

Langenberg, LC, Stekelenburg CM, van der Wal, MBA, Tuinebreijer, WE , van Zuijlen, PPM, Middelkoop, E; “Reconstructieve chirurgie in brandwondlittekens; een eerste overzicht na vijftien jaar follow-up”. Ned. Tijdschr. Plast. Chir; 5 nr 1 p 36-38 (jan 2014)

Langenberg LC, Bakker S; “Anisocoria in a hyperthyroid patient working as an ambulance nurse”, Neth. J. Crit. Care, Volume 18, no 2, 29

Submitted papers

Langenberg LC,Poublon AR, Hofman L, Kleinrensink GJ, Zuidam M, Eygendaal D. Computer-assisted surgical anatomical mapping (CASAM) of the medial antebrachial cutaneous nerves: is there a safe zone for surgery? Journal of hand surgery (European Journal) *(under revision)*

Contribution to research projects

Spek RWA, Schoolmeesters BJA, Oosterhoff JHF, Doornberg JN, van den Bekerom MPJ, Jaarsma RL, Eygendaal D, IJpma F; Traumaplatform 3D Consortium. 3D-printed Handheld Models Do Not Improve Recognition of Specific Characteristics and Patterns of Three-part and Four-part Proximal Humerus Fractures. Clin Orthop Relat Res. 2022 Jan 1;480(1):150-159. doi: 10.1097/CORR.0000000000001921. PMID: 34427569; PMCID: PMC8673959.

Appendix VI: Curriculum Vitae

Lisette Elsenga - Langenberg

EDUCATION	**Education**	
	Secondary school	1998-2000 *st Maartenscollege, Maastricht*; 2000-2004 *st Janslyceum, 's Hertogenbosch:* VWO, profiel N&G (nature/ health) + Spanish and CKV3 (drawing)
	Medical sciences	2004-2011 *Rijksuniversiteit Groningen*
		2005 Propaedeuse, 2008 Bachelor, 2011 Master
	Orthopaedic surgery residencies	April 2016 - August 2023 *Amsterdam area, the Netherlands*
CLINICALEXPERIENCE	**Clinical experience**	
	General surgery house officer(HO)	2011, dec - 2013, dec, *Kennemer Gasthuis, Haarlem*
	Plastic surgery HO	2013, dec – 2014, feb, *Jeroen Bosch ziekenhuis, 's Hertogenbosch*
	Surgical specialties HO	2014, apr – 2014, may, *short stay dept., Vumc Amsterdam*
	Hand surgery HO	2014, jun – 2014, aug, *Centre Hospitalier de la Côte Basque, Bayonne, Frankrijk*
	Emergency dept. HO	2014, sep – 2014, dec, *Sionsberg, Dokkum, Nij Smellinge, Drachten*
	Orthopaedic surgery HO 2	2015, jan – 2015, dec, *Diakonessenhuis, Utrecht*
	Orthopaedic surgery HO	2016, jan – 2016, mrt, *VuMC, Amsterdam*
	Resident in general surgery	2016, apr – 2017, sep, *Spaarne Gasthuis, Haarlem/ Hoofddorp*
	Resident in orthopaedic surg.	2017, oct – 2018, mar, *Spaarne Gasthuis, Haarlem/ Hoofddorp*
		2018, apr – 2019, sep, *Amsterdam UMC, Amsterdam*
		2019, oct – 2020, mar, *Spaarne Gasthuis, Haarlem/ Hoofddorp*
		2020, apr - 2023, aug *Noordwest ziekenhuisgroep Alkmaar/Den Helde*r
	Orthopaedic surgeon	2023 sept - 2023, nov *Visiting orthopaedic surgeon, HOC, Aruba*
	Orthopaedic surgeon, fellow	2023, dec - 2025, jun, Fellow Erasmus Upper extremity Research, Education
		& Care for children and Adults, *Erasmus MC Rotterdam*
EXTRACURRICULAR ACTIVITIES	**Extracurricular activities: Extracurricular non-medical**	
	Secondary school / student jobs: Hostess (Kronenburg), Sailing instructor (it Beaken Heeg, SunSail), field hockey Trainer	
	Groningen, extracurricular students' activities: Students' union Albertus Magnus 2004, Bar tending (Schuit'05-'06) and organization of winter sports for >100 persons.	

EXTRACURRICULAR MEDICAL

Extracurricular Medical	
Event doctor	2014 *Medic Event Support (www.mediceventsupport.nl)*
European Association of Surfing Doctors / Surfing Medicine International	
	2014Conference team annual conference, Sligo, Ireland; Marketing, press, media
	2014 – 2016 Press, social media and website editor, www.surfingmed.com
	2017-2019Head internal communication
	2019- presentHead Surfers’ shoulder expert group
Guest teacher General Practitioner training UMC Utrecht	
	2019-2021twice a year lecturer on pediatric orthopaedics
Guest professor Universidade de a Coruna 2023 lecturer postdoc Surfers health	
App production shoulder Network	
	2022-2023: Patient Journey; patient information SAPS.

HOBBIES AND PERSONAL INTERESTS

Hobbies and personal interests	
Field Hockey	Team: Terriërs 30+ Overgangsklasse
	2025: National 35+ women’s team, Bronze medal, European championships, Valencia, Spain
Sailing	Former CWO instructor youth sailing
	2006: Regatta team 29’er,
	2007: RYA Dinghy and RYA race instructor
	2008: Transatlantic crossing/delivery Jeanneau 49ft,
Surfing	preferably longboarding (8’0); shortboard fish 5’11
Alpine skiing, tour skiing	Avalanche course 2013, freeride and freestyle, Seal skin ski touring certified Advanced Wilderness Life Support (2014, Outdoor Medicine)
Drawing, water color painting	Surf art by Liz; MedSchets: www.medschets.nl

Appendix VII: Dankwoord (acknowledgments)

Het dankwoord is het meest gelezen deel van een proefschrift. En met recht. Dit soort levenswerk-tot-nu-toe komt nooit tot stand zonder de mensen om een promovendus heen.

Tegen de traditie in begin ik met het bedanken van **Hylmar en mijn familie**. Want zonder hen was promoveren echt onmogelijk geweest. Zij moeten dus echt bovenaan. Zonder 'even oppassen om dat artikel af te maken' of de liefdevolle tekst: 'volgens mij moet jij even sporten' had hier geen proefschrift gelegen. Pap, mam, wat ben ik dankbaar voor jullie onvoorwaardelijke support. Annemiek, niet voor niets ben jij vandaag mijn paranimf, ook jij hoort bij dit team. Ik ben trots op het dynamische duo dat mam en jij vormen. Yske en Fedde, wat ben ik er trots op dat jullie samen de kaft van dit boekje hebben gemaakt. Jullie hebben je prachtige armpjes fraai vereeuwigd in en kleurrijk kunstwerk. Diederik, Floor, Olivier en Marilou, dank voor jullie trouwe interesse en het vieren van publicaties.

Het is moeilijk in een paar regels te vatten hoe zeer mijn dank uit gaat naar **Denise Eygendaal** en **Joost Colaris**. Niet alleen hebben zij mij begeleid op wetenschappelijk vlak, ook grote kansen in mijn carrière heb ik aan hen te danken. Bovendien hebben we samen geproost op ons huwelijk. Hoe leuk is dat! Denise, we kennen elkaar al meer dan een decennium. Waarin we ooit begonnen aan de houten tafel in Amphia, daarna koffie dronken in AMC en tenslotte in Erasmus MC in jouw kamer als afdelingshoofd. Maar bovenal heb ik warme herinneringen aan jouw presentatie over koffie in Schotland, speciaalbierproeverij/promotiemeeting in Parijs met Christiaan en afdelingsactiviteiten en feesten in de schildpadvilla. Ik bewonder je persoonlijke interesse, en de manier waarop je momenten waarop jij in de schijnwerper staat, gebruikt om andere mensen een podium te geven. Joost, hoe een kennismaking met een drankje op een boot in Amsterdam niet kan leiden tot prachtige samenwerking! Het 'even afmaken' van een review over radiushalsfracturen bij kinderen, resulteert nu in jouw rol als co-promotor. Ik heb je leren kennen als een humoristische, waardevolle opleider. Tijdens mijn fellowship zijn er veel momenten geweest waarbij ik dankbaar heb mogen leren van je kennis en expertise, maar waarbij ik je ook als persoon enorm ben gaan waarderen. **Christiaan van Bergen**, jou leerde ik kennen in Amphia, maar al eerder kruisten onze wegen een paar keer vanwege een gezamenlijke liefde voor de zee. Dank voor jouw begeleiding en prettige kritische blik bij de totstandkoming van dit proefschrift. Ik hoop daat we er ooit nog eens op proosten op een of ander strand.

Ook **Anna van der Windt** wil ik hier graag benoemen, die als fellowship-opleider mijn klinische begeleiding in het Erasmus MC op zich nam. Ik heb enorm respect voor jouw passie voor het vak en de manier waarop je dit combineert met allerlei neventaken en de (zeer herkenbare) dynamiek van een jong gezin. Het was me een ware eer de eerste EURECA fellow te zijn. Dank ook aan de orthopedisch chirurgen en sportartsen van Erasmus MC en in het bijzonder **Eline van Es** en **Coen Otterspeer**, ik heb jullie enorm gewaardeerd als collega's.

In mijn carrière heb ik vele andere voorbeelden gehad in mijn opleiders, mijn opleiders, de (orthopedisch) chirurgen uit het AMC, Diakonessenhuis, NoordWest Ziekenhuisgroep, Spaarne Gasthuis en (het voormalige) VUMC. Zijn hebben mij gevormd als orthopedisch chirurg en wil ik daarom graag een plek geven in dit dankwoord.

Dank aan al mijn **mede-auteurs**: Joyce Benner, Nazira Bernal Bader, Annechien Beumer, Martine van den Boogaard, Kim van den Ende, Lieke Hofman, Stein Jansen, Gert-Jan Kleinrensink, Koen Koenraadt, Alex Poublon, Max Reijman, Bertram The en Michiel Zuidam. Van vele van jullie heb ik waardevolle input, feedback, agenda-veerkracht gekregen. Ook de **onderzoekscoördinatoren** van de verschillende ziekenhuizen waar ik heb gewerkt verdienen mijn dank. Naast de mensen die al als mede-auteurs zijn genoemd, dank aan Iris van Oost uit Amphia. **Simone Bleeker**, zonder jou had ik me geen weg kunnen banen door alle academische administratie, dank voor je hulp.

Dank aan **Michel van den Bekerom, Edwin Oei** en **Irene Matthijsen** voor het plaatsnemen in de leescommissie van dit proefschrift. Ik ben er trots op dat jullie zo'n gevarieerde expertise meenemen en vanuit verschillende invalshoeken hebben meegedacht. Dank ook aan de andere leden van de commissie: **Gert-Jan Kleinrensink, Charlotte Lameijer** en **Robert-Jan Stolker.** Ik kijk er erg naar uit om met u allen van gedachten te wisselen over het werk dat u nu in handen heeft.

Thanks to all my local and international friends at Surfing Medicine International, I am proud of our friendship that is united through passion for the sport of surfing. I am proud of the research projects that we realized together. But above all, you are an exceptional group of people and I am proud to call you friends. Thank you Kate Batty and Lindsey Dickson for your native speaker contributions, they were highly appreciated. In het bijzonder wil ik hier mijn beste vriendinnetjes Fleur en Marcella bedanken, de lol met het FML ski team is voor het leven en goud waard.

Niet op de laatste plaats dank aan allen die op 25 maart naar het Erasmus MC komen om de verdediging van ruim 10 jaar werk bij te wonen. Ik hoop na afloop met jullie het glas te kunnen heffen.

Financial acknowledgments

The printing and distribution of this thesis was made possible by (in alphabetical order):

- Afdeling Orthopaedische chirurgie en Sportgeneeskunde, Erasmus MC
- Bauerfeind
- Centre for Orthopaedic Research Alkmaar (CORAL)
- ChipSoft
- EMpact
- Erasmus universiteit
- Materialise
- Nederlandse Orthopaedische Vereniging (NOV)
- NoordWest Ziekenhuisgroep
- Operatie & Zorg
- OREC fysiotherapie
- PatiëntPlus
- Pro-Motion Medical
- Stichting FORCE, Amphia
- Werkgroep Schouder en Elleboog (Dutch society for shoulder and elbow surgery)

Appendix VIII: About the author

Lisette Langenberg (1986) lives in Heiloo, the Netherlands, with her husband Hylmar Elsenga and their two children Yske (2018) and Fedde (2020). Bound by their love for the sea, they met via Surfing Medicine International, a group of surf enthusiasts with a medical background. She also enjoys playing field hockey, which she has been doing since she was little.

In 2004, she started studying Medical Sciences (geneeskunde) in Groningen, the Netherlands. She had an interest in other cultures and the organization of medical care in foreign countries, and followed internships in Brazil, Costa Rica, Tanzania and France. She started her residencies to become an orthopedic surgeon in 2016, in the VU medical center in Amsterdam.

At that moment, curiosity for anatomy, biomechanics and potentials for improving current standards, formed the motivation to start researching elbow pathology. She had been drawing anatomical sketches to study and prepare for surgical procedures, and started Medschets.nl, which now turned into a small business. she has illustrated many phd theses, scientific articles and personalized anatomical drawings. All the illustrations in this thesis have been made by Lisette, except the cover.

In the final years of her residencies, Lisette enrolled in a project to optimize communication for patients and healthcare professionals regarding shoulder complaints, by building an application with visuals and animations for patient education. This formed such an inspiration, that she decided to start working at PatientPlus, which is a small company that designs technological solutions to educate patients. In the future, improving patient communication will remain an important goal.