Helsinki University Hospital
Department of Pediatric Surgery
Pediatric Orthopedics and Traumatology
Doctoral Program in Clinical Research
University of Helsinki

# Overriding distal metaphyseal radial fractures in children – Epidemiology, treatment, and outcome

Topi Laaksonen

DOCTORAL DISSERTATION

To be presented for public discussion
with the permission of the Faculty of Medicine of the University of Helsinki,
in Hattivatti -auditorium of New Children's Hospital,
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*To my family - Mona, Unni, Kosti, and Iisa*

# CONTENTS

## ORIGINAL PUBLICATIONS

This doctoral dissertation is based on the following publications:

I Laaksonen T, Kosola J, Nietosvaara N, Puhakka J, Nietosvaara Y, Stenroos A. Epidemiology, treatment, and treatment quality of overriding distal metaphyseal radius fractures in children and adolescents. J Bone Joint Surg Am 2022 Feb 104(3):207-214.

II Laaksonen T, Puhakka J, Kosola J, Stenroos A, Ahonen M, Nietosvaara Y. Most surgeons still prefer to reduce overriding distal radius fractures in children. Acta Orthop 2021 Apr;92(2):235-239.

III Laaksonen T, Puhakka J, Stenroos A, Kosola J, Ahonen M, Nietosvaara Y. Reduction of overriding distal metaphyseal radius fractures in children under ten years of age is not necessary. J Child Orthop 2021 Feb 1;15(1):63-69.

IV Laaksonen T, Stenroos A, Puhakka J, Kosola J, Kautiainen H, Rämö L, Nietosvaara Y. Casting in finger trap traction without reduction versus closed reduction and percutaneous pin fixation of dorsally displaced, overriding distal metaphyseal radius fractures in children under eleven years old: A study protocol of a randomised controlled trial. BMJ Open 2021 May 26;11(5): e045689.

## ABBREVIATIONS

| | |
|---|---|
| AO | Arbeitsgemeinshaft für Osteosynthesegefragen |
| AO-PCCF | AO Paediatric Comprehensive Classification of Long Bone Fractures |
| CT | Computer tomography |
| DAE+VBE | Dorsal above-elbow splint with volar below-elbow splint |
| DIDI | Distal to distal |
| DMRF | Distal metaphyseal radial fracture |
| DMRFOP | Distal metaphyseal radial fracture in overriding position |
| DRUJ | Distal radio-ulnar joint |
| DSMC | Data Safety and Monitoring Committee |
| ED | Emergency department |
| FIN | Flexible intramedullary nail |
| IOM | The Institute of Medicine |
| Li-La | Licht und Lachen für kranke Kinder |
| MAE | Minor adverse event |
| OR | Operation room |
| PICO(T) | Patient/population, intervention/indicator, comparison, outcome, and time element/type of study (optional) |
| PPC | Premature physeal closure |
| PROM | Patient-reported outcome measure |
| PRPR | Proximal to proximal |
| RCT | Randomized controlled trial |
| ROM | Range of motion |
| SAE | Serious adverse event |
| TFCC | Triangular fibrocartilage complex |
| VAS | Visual analog scale |

# ABSTRACT


### *Introduction*

Distal radial metaphysis is the most common fracture location in children and adolescents (Landin 1983). Fracture morphology at distal radial metaphysis varies from stable incomplete torus fractures to complete fractures with different degrees of angulation and shortening (Noonan 1998). Completely displaced fractures in an overriding position with shortening represent the end of the spectrum and reduction of these fractures with angulation, displacement, or shortening has been traditionally recommended (Zamzam 2005). Pin fixation has been advocated, because retaining satisfactory fracture alignment with a cast has been proven difficult (McLauchlan 2002). On the other hand, it has been suggested that distal metaphyseal radial fractures in an overriding position (DMRFOP) in children under 10 years of age could be treated without reduction (Crawford 2012, Marson 2021).

### *Aim*

The aim of Study I was to calculate the incidence of DMRFOP in children under 16 years of age in Helsinki, and to assess retrospectively the overall management and quality of treatment of DMRFOP in our institution. The aim of Study II was to outline the current treatment praxis of DMRFOP in patients under 10 years of age. The aim of Study III was to find out retrospectively whether treatment of DMRFOP in a cast without reduction had obtained results similar to the reduction and pin fixation in prepubertal children in our institution. The aim of Study IV was to design a randomized controlled trial (RCT) comparing casting without reduction to the reduction and percutaneous pin fixation of DMRFOP in children under 11 years of age.

### *Patients and methods*

A total of 113 DMRFOPs in patients under 16 years of age during 2014–19 were gathered from Kids' Fracture Tool, Helsinki. Of these 113 children, 81 were residents of Helsinki. Prescribed treatment, outcome, and adverse events were recorded from the patients' files. Fracture morphology of both radius and ulna were registered from radiographs. Guardians of 100/112 patients replied to a telephone survey to assess their satisfaction of the cosmetic and functional outcome, as well as to the prescribed treatment.

The SurveyMonkey™ website was used as a platform for the survey for surgeons treating fractures in the children. The questionnaire included radiographs of three different DMRFOPs in children under the age of 10. Through multiple-choice questions, respondents (213) were asked to choose their preferred treatment and follow-up protocol.

The outcomes of 12/13 children, whose DMRFOPs were treated at our institution during 2015–17 by cast immobilization, leaving the fractures in bayonet position, were assessed at 2–4 years from the fracture. Twelve age-matched children, whose DMRFOPs were reduced and pin fixed, were chosen as controls.

A noninferiority RCT comparing casting in finger-trap traction without reduction in the emergency department (ED) with the reduction and pin fixation under anesthesia in the treatment of DMRFOP, in children under 11 years of age, was designed.

### *Results*

The mean annual incidence of DMRFOP in the pediatric census population in Helsinki was 1.42/10.000 in 2014–19. Most (73%) DMRFOPs were sustained by children under the age of 11. Reduction in the ED failed in nearly half (46%) of the cases and the rate of secondary intervention was high (56%). Impaired function at follow-up was reported by 6% of the guardians, and forearm asymmetry by 11%. Overall satisfaction to the given treatment was 6.2 on a scale from 1 to 7.

The vast majority (176/213, 83%) of respondents to the web-based survey chose reduction for treatment, whereas 2% chose casting in overriding position in all three presented cases. Pin fixation would have been performed by half (49%) of the surgeons who preferred reduction. There was no consensus regarding treatment and follow-up.

None of the 24 patients in the case control study had visible forearm deformity at follow-up. Forearm and wrist range of motion (ROM) showed no differences between the method of treatment in both injured and uninjured sides, with mean ratios varying between 0.98 and 1.02. All 24 patients had returned to their preinjury activities. Of the 12 surgically treated children, one developed a superficial pin-track infection, and another had a corrective osteotomy.

### *Conclusions*

DMRFOPs are rare, and most of them are sustained by children under 11 years of age. Reduction in the ED is difficult, but functional and cosmetic outcome is generally satisfactory regardless of the treatment method. Treatment of DMRFOP in prepubertal children with reduction and pin fixation does not appear superior to cast immobilization without reduction, although most surgeons still prefer to reduce DMRFOP. A randomized controlled trial, between reduction and pin fixation and the casting treatment, is warranted to verify the results of these studies.

# TIIVISTELMÄ


### *Johdanto*

Värttinäluun alaosan metafyysimurtuma on tavallisin kasvuikäisten luuvamma. Näiden murtumien tyyppi vaihtelee ryppymurtumista paikaltaan siirtyneisiin murtumiin, joissa on kulmavirhe ja lyhentymä. Virheasentoisten murtumien paikalleen asettamista on pidetty hyvän hoitotuloksen edellytyksenä. Värttinäluun alaosan ns. bajonettimurtumien piikkikiinnitystä on suositeltu, koska kipsillä on vaikea pitää murtumaa hyvässä asennossa. Toisaalta on myös esitetty, että alle 10-vuotiailla lapsilla bajonettimurtumat voitaisiin hoitaa kipsillä ilman murtuman paikalleen asettamista.

### *Tavoite*

Ensimmäisen osatyön tavoitteena oli selvittää värttinäluun alaosan metafyysi alueen bajonettimurtumien esiintyvyys alle 16-vuotiailla helsinkiläisillä ja arvioida takautuvasti näiden murtumien hoitoa sekä hoidon laatua. Toisen osatyön tavoitteena oli kartoittaa näiden bajonettimurtumien nykyhoitokäytäntöjä alle 10-vuotiailla lapsilla. Kolmannessa osatyössä tavoitteena oli selvittää takautuvasti, ovatko näiden murtumien hoitotulokset kipsihoidolla, ilman murtuman asennon palauttamista, olleet yhtä hyvät kuin piikkikiinnityksellä omassa sairaalassamme. Neljännen osastyön tavoitteena oli suunnitella satunnaistettu kontrolloitu hoitotutkimus, jotta voidaan selvittää, onko värttinäluun alaosan metafyysin bajonettimurtumien asennon korjaus ja piikkikiinnitys aiheellista prepubertaalisilla lapsilla.

### *Aineisto ja menetelmät*

Lasten murtumarekisteristä (Kids' Fracture Tool, Helsinki) kerättiin vuosilta 2014-19 kaikki (n=113) alle 16-vuotiaiden lasten kyynärvarren alaosan metafyysin bajonettiasentoiset murtumat. Potilaista 81 oli helsinkiläisiä. Toteutettu hoito, hoidon tulokset ja ei toivotut tapahtumat selvitettiin sairauskertomuksista. Murtumien tarkka sijainti mitattiin röntgenkuvista. Sadan (89 %) potilaan huoltaja tavoitettiin puhelimitse, selvittääksemme tyytyväisyyttä annettuun hoitoon ja sen lopputulokseen.

Vallitsevat nykyhoitokäytännöt selvitettiin SurveyMonkey™ internetkyselyllä, jossa vastaajille esitettiin röntgenkuvat kolmen alle 10-vuotiaan potilaan värttinäluun alaosan metafyysin bajonettiasentoisesta murtumasta. Monivalintakysymyksien perusteella vastaajia pyydettiin valitsemaan suosimansa hoitomenetelmä, sekä seurantaprotokolla kuhunkin potilastapaukseen.

Kolmentoista lapsen bajonettimurtuma hoidettiin kipsillä ilman murtuman asennon korjausta vuosina 2015–17. Näistä kahdentoista potilaan hoitotuloksia arvioitiin 2–4 vuoden kuluttua vammasta. Kontrolliryhmäksi

valittiin 12 mahdollisimman samanikäistä vastaavan murtuman saanutta potilasta, jotka oli hoidettu leikkauksella.

Alle 11-vuotiaiden värttinäluun alaosan metafyysin bajonettimurtumapotilaiden sormiloukkumenetelmällä kipsattujen ja piikkikiinnityksellä hoidettujen potilaiden hoitotulosten vertaamiseksi, suunniteltiin hoitotulosten yhdenmukaisuutta vertaileva satunnaistettu kontrolloitu tutkimus.

### *Tulokset*

Alle 16-vuotiaiden helsinkiläisten kyynärvarren alaosan metafyysin bajonettiasentoisten murtumien esiintyvyys oli keskimäärin 1.42/10.000. Suurin osa (73 %) näistä murtumista todettiin alle 11-vuotiailla lapsilla. Murtuman asennon korjaus päivystyksessä epäonnistui lähes puolessa (46 %) tapauksista, ja uusintahoitotoimenpide toteutettiin yli puolelle (56 %) näistä potilaista. Puhelinhaastattelun perusteella vammapuolen kyynärvarren toiminta oli alentunut 6 % potilaista. Kyynärvarret näyttivät eriparisilta 11 % potilaista. Tyytyväisyys annettuun hoitoon oli keskimäärin 6,2 asteikolla 1–7.

Suurin osa (176/213, 83 %) internetkyselyyn vastanneista kirurgeista valitsi hoitomenetelmäksi murtuman paikalleen asetuksen, kun taas 2 % valitsi kipsihoidon bajonettiasentoon kaikissa kolmessa potilastapauksessa. Noin puolet (49 %) vastaajista, jotka halusivat asettaa murtuman paikalleen, olisi myös kiinnittänyt murtuman piikeillä. Seurantakäytännöt vaihtelivat suuresti.

Kenelläkään kolmannen osatyön 24 potilaasta ei todettu seurannassa näkyvää kyynärvarren virheasentoa. Hoitotavasta riippumatta vammautuneen ja terveen yläraajan ranteen ja kyynärvarren liikelaajuuksien suhteiden (vaihteluväli 0.98–1.02) välillä ei todettu eroa. Kaikki 24 potilasta olivat palanneet aiempiin harrastuksiinsa. Yhdellä kahdestatoista leikkauksella hoidetusta potilaasta todettiin pinnallinen piikinjuuri-infektio ja toiselle tehtiin virheasentoon luutuneen värttinäluun korjaustoimenpide.

### *Yhteenveto*

Värttinäluun alaosan metafyysin bajonettiasentoiset murtumat ovat harvinaisia kasvuikäisillä ja niiden esiintymishuippu on 8 vuoden iässä. Näiden murtumien paikalleen asettaminen on vaikeaa. Hoitotulokset ovat pääsääntöisesti hyviä, riippumatta hoitomenetelmästä. Murtuman paikalleen asettaminen on edelleen vallitseva hoitomenetelmä, vaikka piikkikiinnityksestä ei vaikuta olevan etua bajonettiasentoon kipsaamiseen verrattuna prepubertaalisilla potilailla. Olemme suunnitelleet etenevän satunnaistetun seurantatutkimuksen, jonka tulosten perusteella on tarkoitus selvittää, onko värttinäluun alaosan metafyysin bajonettimurtuman paikalleen asettaminen alle 11-vuotiailla aiheellista.

# 1 INTRODUCTION

Distal radial metaphysis is the most common fracture location in pediatric patients (Landin 1983). Most distal radial fractures in children present as incomplete or partial torus or buckle fractures, which are best treated with a removable splint or an orthosis that can be removed at home after a couple of weeks (Perry 2021). Complete fractures with angulation should be reduced and immobilized in a cast or splint with a three-point mold to avoid loss of alignment. Distal metaphyseal radial fractures in an overriding position (DMRFOPs) have been traditionally reduced either under local or general anesthesia (Noonan 1998). Because the retention of reduction with a cast has been proven unreliable, pin fixation has been advocated, especially if the attained alignment is not anatomical (Zamzam 2005).

On the other hand, the remodeling capacity of malunited distal radial metaphyseal fractures in prepubertal children is remarkable and, in fact, up to 30° of sagittal plane angulation has been shown to correct by growth at the speed of 1°–4° per month (Wilkins 2005). Therefore, it has been recently suggested that DMRFOP in children less than 11 years of age could be safely and reliably treated in the emergency department (ED) by casting without formal reduction (Crawford 2012). However, neither patient-reported outcomes nor forearm function after treatment without reduction have been reported, and there is no consensus about optimal treatment of DMRFOP in pediatric patients.

The aim of this study is to calculate the incidence and analyze the morphology of DMRFOP in patients under the age of 16 in Helsinki. The objective of this thesis is also to record the current treatment methods and follow-up protocols, both within our institution and internationally, to assess whether the study of Crawford et al. (2012) has led to any changes in the treatment of DMRFOP. We also aim to evaluate the management and the quality of treatment of these fractures in Helsinki. Our final aim is to design a high-quality randomized controlled trial to compare the casting of the fracture in overriding position in the ED with reduction and pin fixation under anesthesia.

# 2 REVIEW OF THE LITERATURE

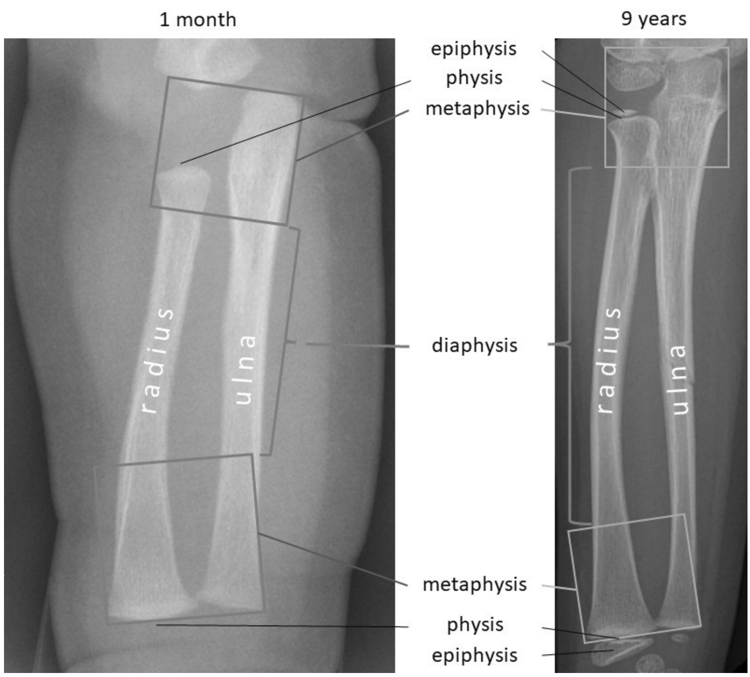
## 2.1 DEVELOPMENT AND GROWTH OF FOREARM

Both radius and ulna are classified as long bones. Cartilaginous long-bone models appear during fetal development. Periosteal capillaries grow into the calcified cartilage of the bone model and form a periosteal bud with osteogenic cells initiating a primary ossification center called diaphysis (Moore 1999). The ossification centers of radius and ulna are visible in radiographs at birth (Alman 2015) (Figure 1).

Secondary ossification centers appear at epiphyses in both proximal and distal ends of the long bones (Figure 1). Distal radius secondary ossification centers appear at the age of 1 year (range 0.25–1.5 years) in both genders, and in the distal ulna at the age of 5 years in girls and 6 years in boys (range 4–9 years) (Herring 2014). The proximal radius secondary ossification center appears at the age of 1 year (range 0.25–1.5 years) in both genders, whereas the proximal ulna apophysis appears approximately at the age of 5 years in girls and 6 years in boys (range 4–9 years) (Herring 2014).

**Figure 1**

**Parts of forearm bones.**



Ossification centers become successively larger from growth and eventually fuse when the bone reaches its adult mature size (Moore 1999). Longitudinal growth occurs at the growing plate, also called physis or epiphyseal line (Moore 1999). Approximately 75% of the radial and 80% of the ulnar longitudinal growth takes place in the distal physis (Noonan 2007, Herring 2014).

Metaphysis is the wide part of a long bone connecting its proximal and distal epiphysis to the shaft, a.k.a. diaphysis (Figure 1). Metaphysis is composed of a thin cortex and trabecular bone, and the cortex of the metaphysis thickens toward diaphysis. Metaphysis in children contains more trabecular bone than metaphysis in adults (Noonan 2007, Peterson 2007).

Periosteum, a fibrous connective tissue membrane, covers dia- and metaphyses of long bones. The outer fibrous layer of the periosteum provides an attachment surface for ligaments, tendons, and muscles. Cells of the inner cambium layer of the periosteum support the lateral growth of the shaft. Periosteum of growing bones in children is thicker than in adults (Noonan 2007, Alman 2015). Diaphyseal bone is nourished by periosteal vessels (Moore 1999).

## 2.2 ANATOMY OF THE DISTAL FOREARM

Radius and ulna are joined together by proximal and distal radioulnar joints (DRUJ), and by a strong fibrous interosseous membrane. Triangular fibrocartilage complex (TFCC) is the main stabilizing structure of the DRUJ (Noonan 2007, Schachinger 2020). TFCC attaches to the distal ulnar fovea and ulnar styloid and to the ulnar side of the radius. In DRUJ, there is a concave joint surface in the radius called the sigmoid notch, and the shape of it varies between people; four different types of it have been described (Jung 2020).

The radius articulates distally with the scaphoid and lunate bones in the radiocarpal joint. The ulna does not have direct contact with carpal bones, because between the ulna and carpal bones is an articular disc, which is part of TFCC (Noonan 2007, Schachinger 2020).

The relative length of the ulna compared to the radius varies among individuals. Most often the ulna is in level with the radius at the radiocarpal joint, or slightly shorter (negative ulnar variance), and measured in millimeters in plain wrist radiographs taken in neutral forearm rotation. There are two different methods to measure ulnar variance in skeletally immature people: 1) the method of Hafner—distal to distal (DIDI), and 2) proximal to proximal (PRPR) (Kox 2020) (Figure 2).

**Figure 2**

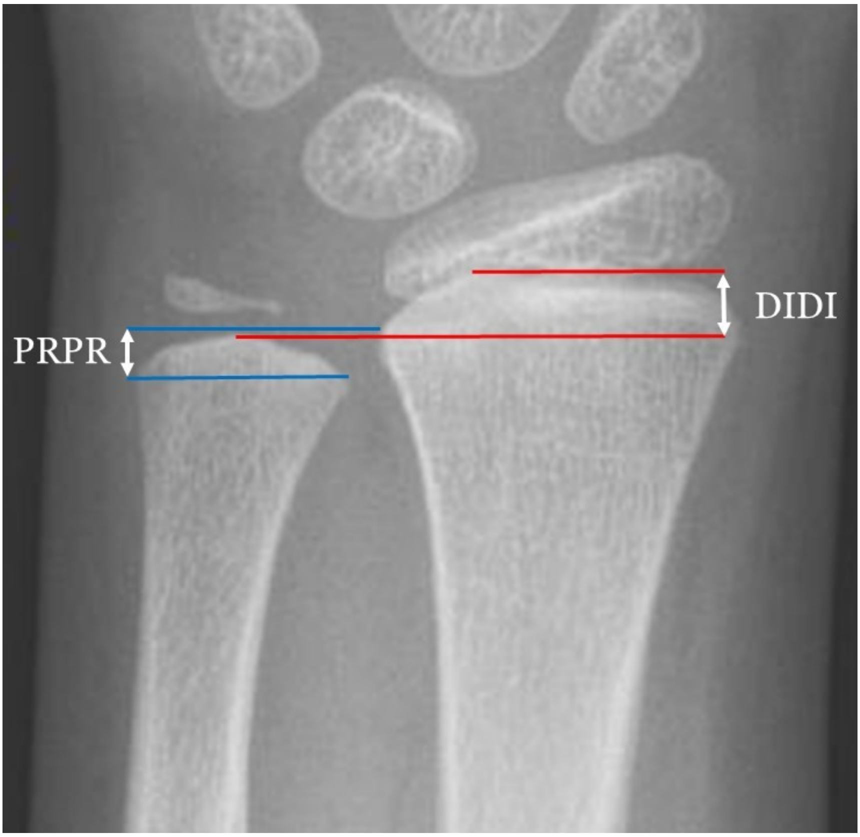
**The methods of Hafner and Kox.**

**Ulnar variance is measured in millimeters between the red and blue lines, drawn at a 90° angle to longitudinal axis of the radius in anteroposterior radiographs of the wrist.**

**In distal to distal (DIDI) method the (red) lines are drawn at the level of the most distal extension of the metaphysis of both radius and ulna.**

**In proximal to proximal (PRPR) method the (blue) lines are drawn at the level where the metaphysis is widest.**

**In this case, DIDI measured 3.8 mm and PRPP 2.9 mm.**

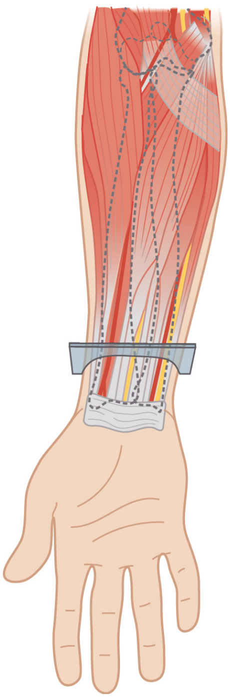


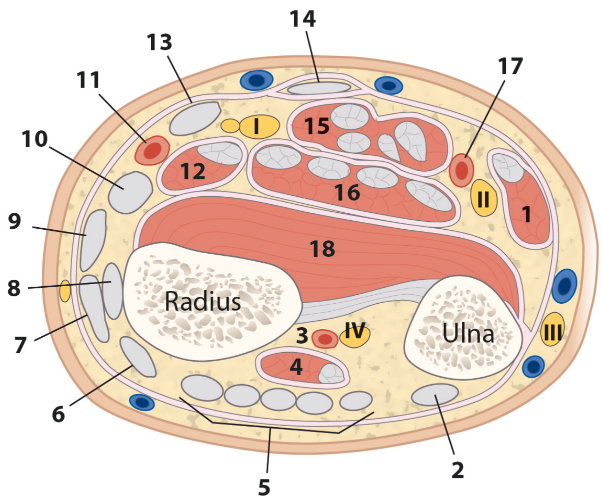

Pronator quadratus is the only muscle joining distal radius to ulna; it is attached to the distal fourth of the anterior surface of the ulna and radius (Moore 1999). The dorsal surface of the distal radius bears no muscle attachments, but has a prominence called the Lister's tubercle that separates radial wrist extensors from thumb and finger extensors (Figure 3).

**Figure 3**

**Cross section and anatomical structures of distal forearm in the level of the most typical position of radial fracture line.**

| arteria | | nerve | | muscle/tendon | |
|---|---|---|---|---|---|
| 3 | posterior interosseus | I | median | 1 | flx carpi ulnaris |
| 11 | radial | II | ulnar | 2 | ext carpi ulnaris |
| 17 | Ulnar | III | ulnar (dorsal branch) | 4 | ext indicis |
| | | IV | posterior interosseus | 5 | ext digitorum and digiti minimi |
| | | | | 6 | ext carpi radialis brevis |
| | | | | 7 | flx pollicis brevis |
| | | | | 8 | ext carpi radialis |
| | | | | 9 | abductor pollicis |
| | | | | 10 | brachioradialis |
| | | | | 12 | flx pollicis longus |
| | | | | 13 | flx carpi radialis |
| | | | | 14 | palmaris longus |
| | | | | 15 | flx digitorum superficialis |
| | | | | 16 | flx digitorum profundus |
| | | | | 18 | Pronator quadratus |





## 2.3 FUNCTION OF THE FOREARM AND WRIST

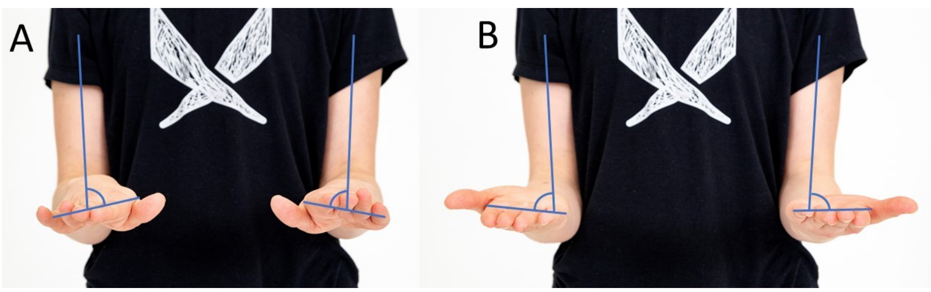
### 2.3.1 PROSUPINATION OF THE FOREARM

In the anatomic position, radius and ulna are next to each other: radius on the lateral side, and forearm in maximal supination (external rotation). In pronation (internal rotation), the curved radius turns over the ulna, anteriorly tightening the interosseous membrane (Noonan 2007). Forearm rotation takes place in proximal- and distal radioulnar joint. The longitudinal axis of that rotational movement goes from the center of the radial head to the fovea of the ulnar head (Kleinman 2007, Snow 2014). Ulnar movement is minimal during forearm rotation, because the humeroulnar articulation is a relatively stable hinge joint, according to Tynan et al. (2000). Muscles that produce forearm movements are numbered in Table 1.

Normal active range of both pronation and supination have been reported to be 90° in elbow flexion (Iyer 2012). Morley et al. (1981) reported that 50° of pronation and supination is enough for adults to perform normal daily activities (Figures 4A and 4B), however, according to Raiss et al. (2007), the required range of forearm rotation is slightly larger than that (pronation 55° and supination 72°). Sardelli et al. (2011) claimed that 65° of pronation and 77° of supination is needed for keyboarding and for mobile phone use, and Valone et al. (2019) suggested that children and adolescents under 18 years of age need 53° of pronation and 63° of supination to perform modern contemporary tasks.

**Figure 4**

**Pronation (A) and supination (B) are measured with the patient's shoulders in anatomic position, elbows in 90° flexion, and wrists in neutral position (Iyer 2012).**



### 2.3.2 EXTENSION–FLEXION MOVEMENT OF THE WRIST

Extension–flexion motion of the wrist (Figure 5) is a complex process that takes place in radio- and midcarpal joints (Moojen 2003, Gardner 2006, Stoesser 2017). Wrist extension (Table 1) occurs mostly in the midcarpal joint and flexion in the radiocarpal joint (Stoesser 2017).

Normal flexion has been reported to be up to 80° and normal extension up to 70°, respectively (Iyer 2012). Most contemporary tasks of the upper limbs require a compound movement of the shoulder, elbow, forearm, wrist, and fingers. The wrist usually moves either to flexion and ulnar deviation or to extension and radial deviation; these movements are called "dart-thrower's motion" in combination (Gardner 2006).

Klum et al. (2012) reported 64°–67° of mean active extension and 67°–74° of mean active flexion of the wrist in young adults. According to Gates et al. (2016), 40° of wrist extension and 38° of wrist flexion is enough to perform daily activities, but in the study of Aizawa (2010), approximately 76° of wrist flexion is needed to be touching the ipsilateral axilla, which is important to individuals with only one functional upper limb.

**Figure 5**

**There is no standardized way to register wrist extension and flexion. One option would be to measure active wrist extension (A) and flexion (B) from photographs, as shown here in a 12-year-old child, who had 60° extension and 85° flexion of her right wrist when her forearm was in pronated position.**

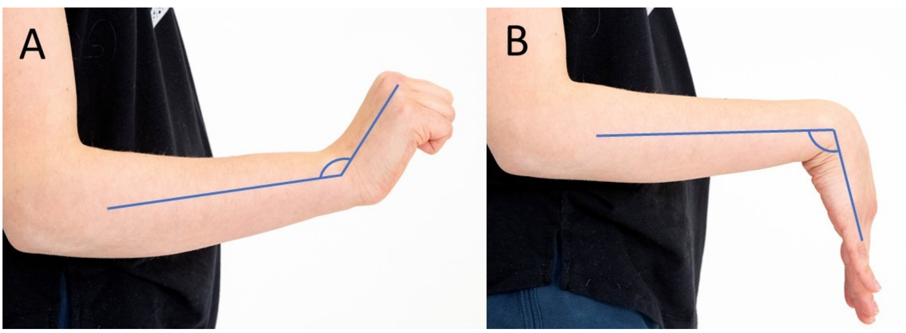


**Table 1**

**Forearm rotator and wrist extensor/flexor muscles and their motor nerves (Noonan 1998, Moore 1999).**

| Muscle (innervation/peripheral nerve) | Pronation | Supination | Extension | Flexion |
|---|---|---|---|---|
| Pronator teres (median) | + | | | |
| Pronator quadratus (median) | + | | | |
| Biceps brachii (musculocutaneus) | | + | | |
| Supinator (radial) | | + | | |
| Extensor carpi radialis longus and -brevis (radial) | | | + | |
| Extensor carpi ulnaris (radial) | | | + | |
| Extensor digitorum, -indicis, -digiti minimi, -pollicis longus (radial) | | | + | |
| Flexor carpi radialis (median) | | | | + |
| Palmaris longus (median) | | | | + |
| Flexor digitorum superficialis 2–5, -pollicis longus, -digitorum profundus 2–3* (median) | | | | + |
| Flexor carpi ulnaris, -digitorum profundus 4–5** (ulnar) | | | | + |

*Lateral part, **Median part

### 2.3.3 GRIP STRENGTH

Grip strength has been regarded as a good indicator of hand function (De Smet 2001), which can be measured with a hydraulic hand dynamometer (Mathiowetz 1984, De Smet 2001, Hepping 2015, McQuiddy 2015). The American Society of Hand Therapists has described a standard way to perform the measurement (Figure 6). Grip strength is recorded in kilograms as the best effort of three attempts (Hepping 2015, McQuiddy 2015).

Grip strength has large variability among children, but it increases with age. Length of the upper extremity and body weight correlate positively to maximum grip strength (Mathiowetz 1984, Häger-Ross 2002), and boys have on average a higher grip strength than girls (Mathiowetz 1984, De Smet 2001, Häger-Ross 2002, McQuiddy 2015). Grip strength of the right dominant hand is generally about 10% better than in the left nondominant hand (Häger-Ross 2002, Hepping 2015), and this difference in grip strength between dominant and nondominant hands might be smaller in children with left-sided hand dominance (Hepping 2015, De Smet 2001, Häger-Ross 2002, McQuiddy 2015). However, the ratio of grip strength is considered a reliable way to assess hand function (De Smet 2001, McQuiddy 2015).

**Figure 6**

**Grip strength is measured with a handheld dynamometer (Jamar®). During measurement the patient should sit in a chair with her back off of the chair, feet on a floor, shoulder in anatomic position, elbow in 90° flexion, forearm in neutral rotation, and wrist in neutral or in slight extension (0°–30°) and in slight ulnar deviation (0°–15°) (Fess 1992, De Smet 2001).**

## 2.4 DISTAL RADIAL FRACTURES

### *2.4.1 Incidence and injury mechanism*

The distal radius is the most common site of fracture in children and adolescents, comprising 23%–31% of all pediatric fractures (Landin 1983, Lyons 1999, Ward 2006, Rennie 2007, Hedström 2010, Lempesis 2019). The reported annual incidence of distal radial fractures in children under the age of 16 in Nordic countries is around 50–60/10 000, and approximately one-fifth of these fractures are displaced (Brudvik 2003, Hove 2008, Mäyränpää 2010, Lempesis 2019). Complete metaphyseal fractures of the distal radius take place during falls on an outstretched hand, from bending, rotational, or shear forces (Do 2003, Bae 2008, Hove 2008) (Table 2).

**Table 2**

**The incidence of distal forearm fractures in pediatric patients in previous studies compared to our data from Kids' Fracture Tool, Helsinki.**

| | Time period | Patients' age | Patients (n) | Fractures (n) | Forearm fractures (n) | Fracture incidence / 10,000 / year | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | All | Forearm | Distal forearm | Overriding position |
| Landin (1983) | 1975–1979 | <17 | 4115 | 4621 | 970 | 212 | 45 | 37 | - |
| Rennie (2007) | 2000 | <16 | 2168 | 2198 | - | 202 | 83 | 67 | - |
| Meling (2009) | 2009 | <16 | - | 964 | 639 | - | 23 | 12 | - |
| Schalamon (2011) | 12/2004–10/2007 | <19 | 3339 | 3421 | - | - | - | - | - |
| Joeris (2017) | 2009–2011 | <18 | 2203 | 2292 | - | - | - | - | - |
| Kids' Fracture Tool, Helsinki | 2014–2019 | <16 | 10,954 | 12,044 | 4219 | >93 | >31 | >22 | 1.42 |

**The relative proportion of various kinds of forearm fractures in children. The proportion of different forearm fractures of all children's fractures are in brackets.**

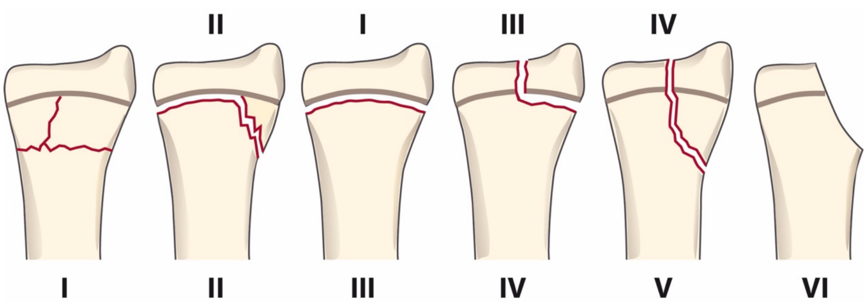
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Proximal** | **Forearm** | | 6.9% | 6.4% | 8.3% (2.5%) | 10.3% | 11.9% |
| | Radius + ulna | | | | 1.6% (0.5%) | | |
| | Radius | 4.4% (1.2%) | | | 4.6% (1.4%) | 5.2% | 6.9% |
| | Ulna | | | | 2.1% (0.6%) | 5.1% | 5.0% |
| **Diaphyseal** | **Forearm** | 12.5% (3.4%) | 13.2% | 42.1% | 13.4% (4%) | 7.4% | 23.1% |
| | Radius + ulna | | | | 10.1% (3%) | | 18.3% |
| | Radius | | | | 0.9% (0.3%) | 3.4% | 3.0% |
| | Ulna | | | | 2.4% (0.7%) | 4.0% | 2.0% |
| **Distal** | **Forearm** | 83.2% (22.7%) | 80.0% | 51.3% | 78.3% (23.5%) | 81.8% | 65.0% |
| | Radius + ulna | | | | 51.0% (8%) | | 25.8% |
| | Radius | | | | 26.5% (15.3%) | 80.6% | 39.2% |
| | Ulna | | | | 0.8% (0.2%) | | |

### *2.4.2 Physeal fractures of the distal radius*

Fractures that affect the growth plates of long bones are called physeal fractures. There are seven different classifications for physeal fractures (Peterson 2007), of which the Salter-Harris (1963) classification is the most widely used, although the Peterson (1994) classification is more logical and comprehensive (Figure 7).

**Figure 7**

**Peterson (roman numerals below) and Salter-Harris (roman numerals above) classification systems of physeal fractures. Salter-Harris type V fracture represents a compression injury of the physis; this type of physeal injury is controversial and is not shown here (Peterson 1981).**




### *2.4.3 Types of distal metaphyseal radial fractures (DMRF)*

Incomplete fractures

Incomplete metaphyseal, torus, or buckle fractures comprise most distal forearm fractures in skeletally immature patients. These fractures are a combination of a compression of the trabeculae on the compression side and minimal plastic deformation on the distraction side of the injured metaphysis. Instead of a fracture line through the metaphysis, a buckle on the thin metaphyseal cortex is seen on the compression side of the bone. The distraction-side cortex looks either intact or is minimally bent, and there is often some swelling around the distal forearm, but no clinically obvious deformity. Torus fractures are thus stable and occur exclusively in children (Noonan 1998, Zimmerman 2004, Perry 2021).

Complete fractures

Complete fractures break the bone in at least two fragments, and a visible fracture line traversing through the metaphysis can usually be seen on radiographs. Complete fractures are unstable, with varying degrees of angulation and direction of displacement (Noonan 1998). Completely displaced fractures have shortening with the fracture fragments in an overriding or bayonet position, because of the tension of the wrist and finger extensor and flexor muscles (Do 2003, Crawford 2012, Marson 2021). The periosteum is ruptured on the fracture's distraction side, but often stays intact on the fracture's concave compression surface (Noonan 1998, Zimmerman 2004).

### *2.4.4 Diagnosis*

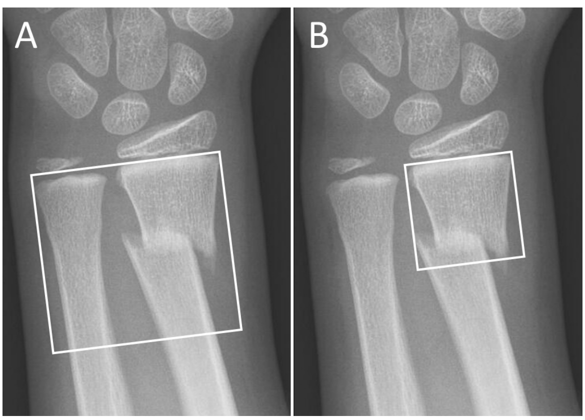
Angulated and displaced distal forearm fractures are clinically obvious because of swelling and deformity. Radiographs taken in both AP and lateral views can define definite diagnosis, fracture classification, and its alignment. Computer tomography (CT) is rarely needed in pediatric metaphyseal fractures.

### *2.4.5. Methods to define metaphysis*

Metaphysis of distal radius has been classified by the method of Arbeitsgemeinshaft für Osteosynthesegefragen (AO) Pediatric Comprehensive Classification of Long Bone Fractures (AO-PCCF), published in 2017 (Joeris 2017). Distal radial and ulnar metaphyses extend more proximally according to AO-PCCF method (Figure 8A) than the way they are presented in the Licht und Lachen für kranke Kinder (Li-La) classification for pediatric long bone fractures, published by Schneidmüller in 2011 (Figure 8B).

**Figure 8**

**AO-PCCF (A) and Li-La (B) classification methods for defining the metaphyseal area of distal radius in AP radiographs. Fractures shown in boxes are classified as metaphyseal fractures.**



## 2.5 TREATMENT OF DMRFOP

### *2.5.1 Nonsurgical treatment*

Reduction and cast immobilization of DMRFOP has been the gold standard of the treatment, which can be performed in the ED with local anesthesia (with or without conscious sedation) or under general anesthesia (McLauchlan 2002, Zamzam 2005, Crawford 2012). Crawford et al. (2012) accepted the overriding position in children under 11 years of age with distal radial metaphyseal fractures and immobilized the injured wrist with a molded short arm-cast to correct the axial alignment of the fractured bone(s).

The recommended length of cast immobilization of distal forearm fractures in children and adolescents varies from 3 to 8 weeks (Noonan 1998, Zimmermann 2004, Bohm 2006, Crawford 2012). There is no consensus regarding whether the above- or below-elbow cast or splint should be used, although Bohm et al. (2006) discovered in an assessor-blinded randomized controlled trial that below-elbow casts perform as well as above-elbow casts in maintaining reduction of DMRF in pediatric patients. Weekly radiographic follow-up has been advocated due to a high risk of the loss of reduction during cast immobilization, but there is no consensus concerning how many controls are necessary (Noonan 1998, Zamzam 2005, Bohm 2006, Bernthal 2015).

### *2.5.2 Surgical treatment*

Several authors have recommended percutaneous pin fixation of displaced DMRF, especially if the attained reduction is not anatomic (Miller 2005, Zamzam 2005, Schneider 2007, Van Leemput 2009, Ramoutar 2015). Osteosynthesis is usually performed with one to two smooth pins purchasing both fracture fragments (Ramoutar 2015). The AO Foundation recommends avoiding the distal radial physis, because of a potential risk of causing an iatrogenic premature physeal closure (PPC) (AO Surgery Reference). Most surgeons use retrograde pinning either through the radial styloid or just proximal to the lateral distal radial physis with a second pin through Lister's tubercle (Tryfonidis 2010, Lee 2013, AO Surgery Reference) (Figure 9). Trans-radioulnar pin fixation has also been described (Jung 2007).

Closed reduction of a DMRFOP can rarely prove to be impossible even under anesthesia, either because of the fracture morphology or the soft tissue interposition, for example, pronator quadratus muscle (Noonan 1998) (Figure 10). In these cases, percutaneous reduction with, for example, a dissector inserted via a short dorsal incision at the fracture level can be attempted (Varga 2017, Du 2019). Open reduction, which is mainly performed via a modified Henry's approach (Conti 2016), is justified in patients over 13 years of age if closed reduction fails (Pannu 2015). Plating is a good option for osteosynthesis after open reduction, especially in adolescents (Pannu 2019, van Egmond 2019). Flexible intramedullary nails (FIN) have also been used in treatment of DMRFOP located at the level of the meta-diaphyseal junction (Kim 2017, Varga 2017, Du 2019).

Osteosynthesis with pins or FIN is not very stable, and further stability to guarantee satisfactory fracture union should be provided with a cast up to 4–6 weeks from surgery (Ramoutar 2015). A removable splint or an orthosis is more practical for children and adolescents whose DMRFOP have been fixed with a plate (Miller 2005, Mostafa 2009, Du 2019, van Egmond 2019).

**Figure 9**

**DMRFOP has been reduced and fixed with two smooth 1.6 mm pins drilled retrograde through the radial styloid (A) and Lister's tubercle (B) in a 9-year-old patient.**

**Sensory nerve branches and tendons at risk in pin fixation of DMRFOP. This patient could not extend his thumb interphalangeal joint postoperatively, because the pin inserted at Lister's tubercle (B) had pierced his long thumb extensor tendon.**

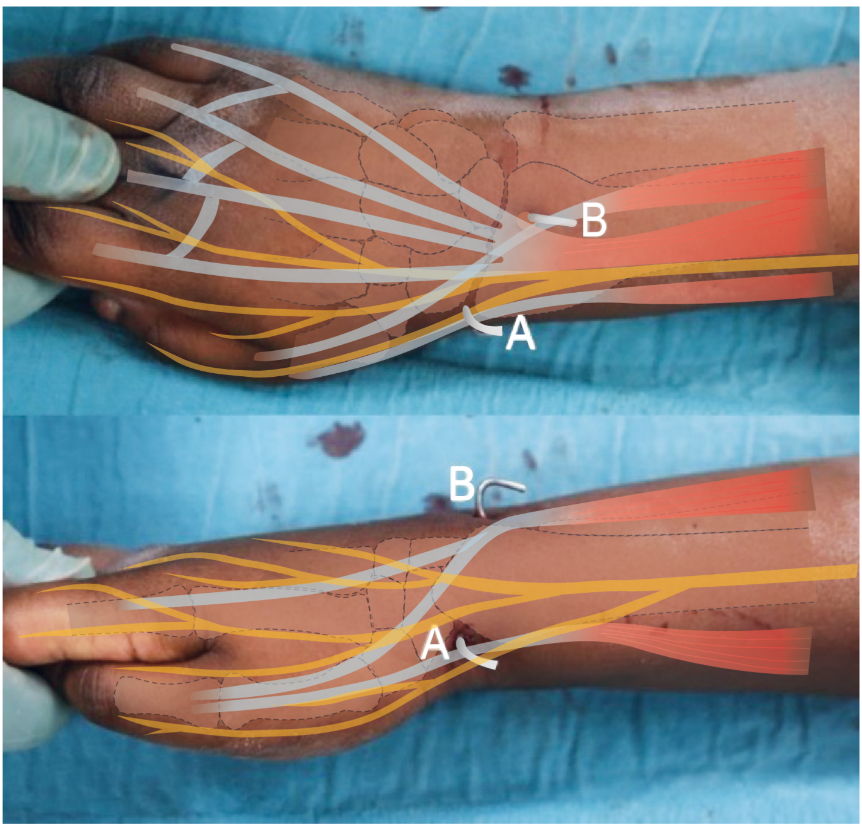
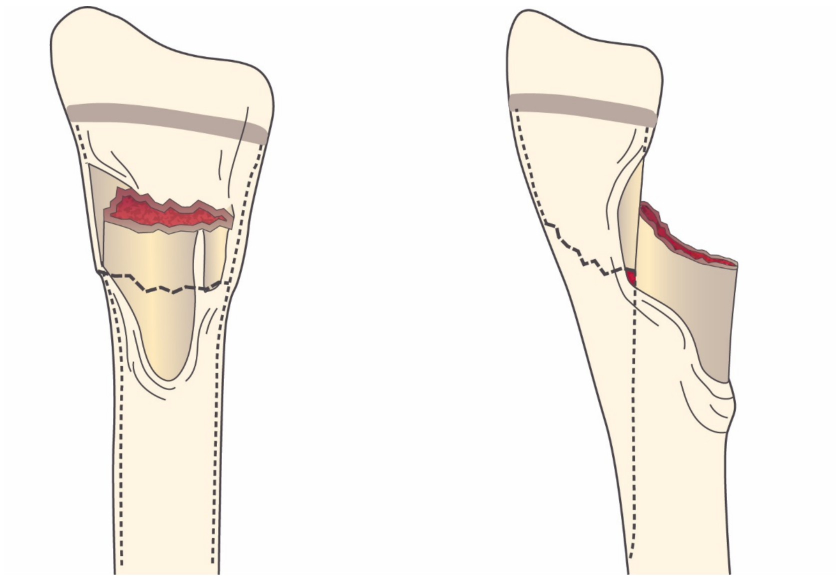


**Figure 10**

**Overriding distal radial metaphyseal fracture in a typical position with the distal-fracture fragment displaced dorsally. Dorsal periosteum of the radius is mainly intact, which is important for fracture union and the remodeling process.**



## *2.5.3 Adverse events of the treatment*

### Loss of reduction

Loss of reduction of DMRFOP during immobilization is common (14%–91%), even if the cast or splints have been molded properly (Gibbons 1994, Miller 2005). The predictors of loss of reduction are 1) complete displacement of the fracture, 2) lack of anatomical reduction, 3) improper three-point molding of the cast, 4) ipsilateral distal ulnar fracture, and 5) reduction without general anesthesia (Proctor 1993, Haddad 1995, Zamzam 2005, Bohm 2006, Hang 2011). Several cast indexes measured from radiographs have also been described to assess the risk of loss of reduction (Ravier et al. 2020).

### Pin fixation-related problems

A typical complication after percutaneous pinning is superficial pin-site infection (3.8%–5.9%), which usually heals with local treatment and per oral antibiotics, most definitely after pin removal (Stahl 2001, Battle 2007). Deep pin-related infections, such as osteomyelitis or septic arthritis, are rare (0.4%–2%) (Stahl 2001, Battle 2007).

Stahl et al. (2001) reported that the most common pin-related complication is loosening of the pin due to suboptimal placement as a technical failure. Pin loosening increases the risk of pin migration during immobilization (Stahl 2001, Firoozabadi 2013, Marson 2021); in the worst case this would necessitate pin removal under general anesthesia (Battle 2007).

Other pin-related complications in the treatment of distal forearm fractures that have been described are 1) lesion of the superficial sensory branch of the radial nerve, 2) extensor tendon lacerations, and 3) physeal growth arrest of the distal radius (Stahl 2001, Miller 2005, Fujihara 2020).

Skin irritation at the ends of FIN have been reported in 10%–13% of patients (Varga 2017, Du 2019), but postoperative infections are rare (Kim 2017).

#### Compartment syndrome

Compartment syndrome is a rare complication, which is injury- rather than treatment-related. The forearm is the second-most common location of compartment syndrome in children, and it usually affects anterior forearm muscle compartments (Lin 2020). Acute carpal tunnel syndrome is also a rare complication of distal radial fractures (Pannu 2015).

#### Functional deficits

Malunion of forearm fractures can limit forearm and wrist motion, however, up to 39° radial and dorsal, and 22° volar angulation, can remodel in under 11 years of age children so well that forearm and wrist function will return to normal (Roth 2014, Akar 2018).

DRUJ instability can develop as a late sequela of malunited distal radial fracture, which has been reported to be diagnosed at mean 2–3 (range 0–18) years after the fracture in adolescents (mean age 13, range 12–17 years) (Bowers 2012, Andersson 2013, Miller 2018).

## 2.6 HEALING OF DMRFOP

Fracture healing in skeletally immature patients has been described to occur in three phases. At first, a hematoma containing fibrin is formed at the site of fracture in the inflammatory phase, then fibrin will be rapidly replaced by a collagen scaffold. The proteins in the hematoma stimulate cell differentiation to angio-, fibro-, chondro- and osteoblasts, which are needed for new bone formation. The second, reparative, phase takes 2–3 months, during which callus is formed by both endosteal- and intramembranous ossification. Callus gives temporary stability between the bone fragments but is not as rigid as the normal bone is. During the last phase, remodeling, callus is gradually replaced by new bone over the next several months (Wilkins 2005).

Distal radial physis is responsible for about 80% of radius longitudinal growth (Noonan 1998). Growth of the distal radial physis is stimulated by fractures, and possible axial angulation leads to asymmetric activity of the growth plate, producing more new bone on the convex side of the metaphysis (Ryöppy 1974, Larsen 1988). Most (75%) remodeling of pediatric long bone fractures occurs because of this phenomenon. Periosteal new bone formation can also lead to minor angular deformity corrections at the fracture site (Figure 10). Distal metaphyseal fractures in children thus have a vast potential for remodeling; this achieves the greatest success the shorter the distance from distal radial physis to the fracture level (Friberg 1979). It has been estimated that, in children with 2–5 years growth remaining, up to 23° coronal and 30°–35° sagittal angulation will remodel fully (Wilkins 2005, Lynch 2020) (Figure 11).

Most DMRFOPs are displaced dorsally, and the anterior periosteum is torn. The intact dorsal periosteum is elevated off the cortex, forming a periosteal sleeve filled with blood (Wilkins 2005) (Figure 10). Rapid intramembranous callus forms within this pocket, remodeling the residual deformity caused by the overriding position of the fracture (Noonan 1998). Do et al. (2003) accept up to 15° of angulation and 10 mm shortening in children with 2 years or more growth left who have sustained a DMRFOP. According to Wilkins et al. (2005), an overriding position of the radial fracture could be accepted in children of up to 12 years of age if the axial alignment is nearly anatomical. Crawford et al. (2012), Marson et al. (2021), and Martinelli (2021) have reported 100% fracture union, satisfactory remodeling, and full range of wrist motion in 1-year follow up in children under 11 years of age, whose DMRFOPs were cast without reduction. The good outcomes in DMRFOP in prepubertal children treated with reduction and casting is at least partially due to fast remodeling of residual deformity for the period of 4–13 months after fracture healing (Do 2003, Miller 2005).

**Figure 11**

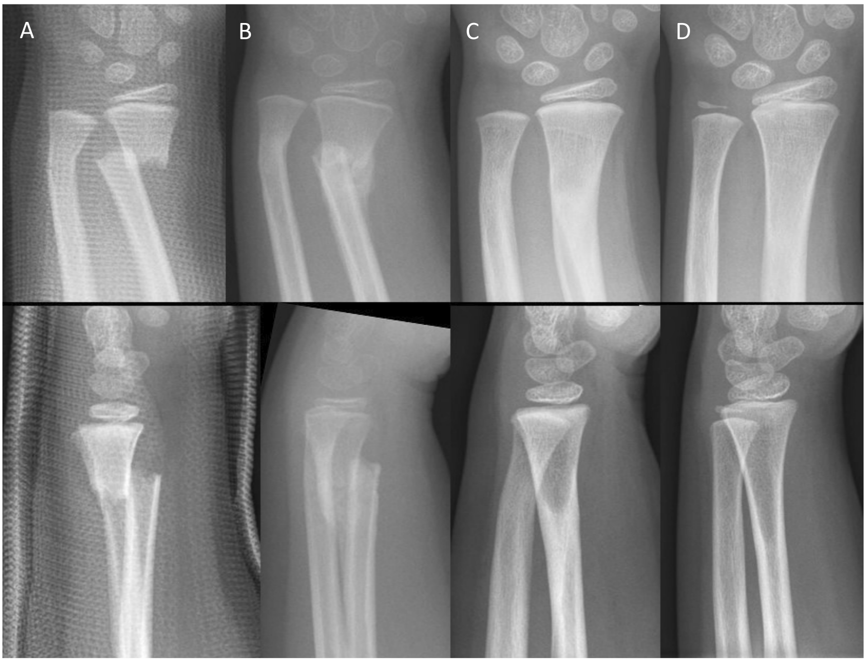
**Remodeling of the distal forearm in a 5-year-old child who sustained DMRFOP.**

**A** **Axial alignment in frontal and sagittal planes after application of dorsal and volar splints.**

**B** **Frontal and sagittal alignment 5 weeks from injury. Callus has filled the periosteal sleeve.**

**C** **Rapid correction of the deformity by asymmetric physeal growth, with an obliquely oriented Harris line in the AP view.**

**D** **Complete restoration of the axial alignment is evident at 18 months from the fracture.**




## 2.7 QUALITY OF FRACTURE TREATMENT

Merriam-Webster's dictionary defines the word "quality" as the following: 1) how good or bad something is, 2) a characteristic or feature that someone or something has: something that can be noticed as a part of a person or thing, and 3) a high level of value or excellence. Depending on the (scientific) discipline in question, variable definitions have been introduced for "quality" (Table 3).

**Table 3**

**Variable definitions for “quality,” depending on the field.**

| Discipline | Definition for ”quality” |
|---|---|
| Business/Industry | The noninferiority or superiority of something<br>Fitness for use (Juran 1979)<br>Conformance to requirements (Crosby 1979) |
| Philosophy | An attribute or a property |
| Physics | In response theory |

**https://en.wikipedia.org/wiki/Quality**

Outcome of fracture treatment has been traditionally assessed by the quality of reduction and alignment of the fracture at union in radiographs. Other methods used to evaluate quality of fracture treatment are 1) range of motion in the joints of the affected limb, 2) length of time to return to daily or recreational activities, 3) patient-reported outcome measures, and 4) the number of reoperations. An example of utilizing all these assessment methods is the recently begun study, “PedORTHO-A Prospective Multicenter Observational Registry of Paediatric Orthopaedic Trauma and Health Outcomes in Skeletally Immature Children” (Vidakovic 2021). Also, complications of treatment and other adverse events have been included in reports assessing treatment quality (McLauchlan 2002).

The Institute of Medicine (IOM) (Washington, USA) defined that high-quality care is safe, timely, effective, efficient, equitable, and patient centered (Rockville 2018). Even if “patient centered” has been cited as being an important way to evaluate treatment quality, there are no validated patient-reported outcome measures (PROMs) targeted to pediatric fractures that assess the patient’s physical function, nor the quality of daily living (Marson 2020). Table 4 outlines one way to assess all the aspects of high-quality care presented by IOM in pediatric fracture management.

**Table 4**

**Evaluation options for quality assessment of pediatric fracture care by IOM's definition of high-quality treatment. Previous studies in brackets.**

| IOM value | Meaning for patient/guardian in fracture care | Measuring instrument in fracture care |
|---|---|---|
| **Safe** | -no iatrogenic injuries<br>-no unnecessary interventions | -number of complications or adverse events (McLauchlan 2002) |
| **Timely** | -primary and definitive treatment will be given without delay | -operation time (Jung 2007)<br>-hospitalization time (Jung 2007) |
| **Effective** | -prescribed treatment enables shortest possible healing process | -immobilization time (Crawford 2012)<br>-return to daily activities (Axibal 2020) |
| **Efficient** | -minimizing pain during healing<br>-treatment interventions are as minimally invasive as possible | -patient-reported outcome measures<br>-cost of given treatment options (Crawford 2012, Martinelli 2021) |
| **Equitable** | -patients treated in their order of medical urgency by best possible treatment options | -use of traffic-light system in operation department |
| **Patient (family) centered** | -understandable information and option to take part in decisions<br>-patient/guardian evaluation of the healing process | -feedback of patient and guardian (Crawford 2012)<br>-patient-reported outcome measures |

## 2.8 CONCLUSIONS FROM THE LITERARY REVIEW

Incidence of DMRFOPs in children and adolescents is unknown. Traditionally, these fractures have been treated with reduction and casting with or without pin fixation. Loss of reduction during cast immobilization is frequent without fixation, especially after nonanatomic reduction, hence, pin fixation of DMRFOP under general anesthesia has been advocated.  However, there is no empirical evidence of whether this would provide any benefit compared with simple casting of DMRFOP.

Remodeling potential of malunited DMRF in children is vast. Deformities with up to 10 mm shortening, 35° dorsal-, and 23° coronal angulation have been reported to remodel within 4–13 months after fracture union (Noonan 1998, Do 2003, Crawford 2012, Marson 2021).

Pl´anka et al. (2005), Crawford et al. (2012), Marson et al. (2021), and Martinelli et al. (2021) have previously reported good outcomes without complications in children under 12 years of age in DMRFOP treatment with no reduction, by casting their fractures in an overriding position.

# 3 AIMS OF THE PRESENT STUDY

The aim of the present study was to investigate the rationale of the current treatment strategy for children and adolescents with distal metaphyseal radial fractures in overriding position.

The specific aims of the project were as follows (roman numerals refer to the original publications):

I To calculate incidence in Helsinki city residents under 16 years of age and assess management and quality of treatment of overriding distal metaphyseal radial fractures in New Children's Hospital.

II To survey current preferred treatment strategies in children under 10 years of age for overriding distal metaphyseal radial fractures.

III To assess the feasibility of treating overriding distal metaphyseal radial fractures in children under 11 years of age without reduction, with cast immobilization in overriding position, by comparing the midterm results of this strategy to the conventional treatment strategy of reduction and pin fixation.

IV To describe the background, rationale, and execution of a randomized controlled trial comparing cast treatment without formal reduction vs. conventional treatment of formal (anatomic) reduction and (rigid) pin fixation in prepubertal patients with distal metaphyseal radial fracture in overriding position.

# 4 PATIENTS AND METHODS

## 4.1 STUDIES I, III, AND IV

The design and characteristics of studies I, III, and IV are summarized according to PICO(T) elements (Richardson 1995), which include the following: **P**atient/**P**opulation, **I**ntervention/**I**ndicator, **C**omparison, **O**utcome, and **T**ime element (optional) or **T**ype of study (Table 5).

**Table 5**

**Characteristics of the studies according to the PICO(T) criteria.**

| | Study I | Study III | Study IV |
|---|---|---|---|
| **P**atients | 112 | 12+12 | 30+30 |
| Mean age (years) | 8.8 (range 3.4–15.8) | 6.9 (range 4.8–9.9) | <11 |
| Gender (boys/girls) | 74/38 | 17/7 | |
| Injured side (right/left) | 55/58 | 8/16 | |
| **I**ntervention/**C**omparator | Analysis of treatment and mid-term telephone survey | Cast-treated vs. pin-fixed fractures | Cast-treated vs. pin-fixed fractures |
| -Forearms prosupination ratio | | X | X (primary **o**utcome) |
| -Wrists extension-flexion ratio | | X | X (primary **o**utcome) |
| -Passive extension of the wrists | | X | X |
| -Grip strength | | X | X |
| -QuickDASH | | X | X |
| -PedsQL | | X | X |
| -Pain medication | X | | X |
| -Deformity measurements | X | X | X |
| -Reinterventions | X | X | X |
| -Length of the immobilization | X | X | X |
| -Harms and complication of treatment | X | X | X |
| -Guardian satisfaction | X | X | X |
| **O**utcomes | Summarized in the Results section | | |
| **T**ime, collection of the patients | 2014–19 | 2015–17 | Started June 2020 |
| **T**ime, follow-up (years) | 1.5–7.2 | 2.5–4.5 | 1 |
| **T**ype of study | Prospective cohort study | Case-control study | Randomized controlled trial (study protocol) |

### 4.1.1 PATIENTS

**In studies I and III,** the patients (Table 5) were collected by registry software, Kids' Fracture Tool (New Children's Hospital, Helsinki, Finland and BCB Medical, Turku, Finland). When injured patients are admitted to the ED their data is entered into the registry, and additional data on treatment and recovery is added at all phases of fracture treatment. The statistical yearbook of Helsinki was utilized for calculations of annual incidence of DMRFOP in residents of Helsinki under 16 years of age.

In Study I, the radiographs of all the patients with distal- or diaphyseal forearm fracture (ICD-10 codes S52.4-6) were scrutinized to ensure diagnosis of metaphyseal radial fracture in overriding position. The direction of displacement in the DMRFOP was recorded in the primary radiographs. The morphology of the fracture was classified as horizontal, oblique, or comminuted. The type of the distal ulna fracture was analyzed to be styloid avulsion, physeal (classification by Peterson), torus, greenstick, complete (translation <100%), or overriding. In the radius the shortest distance from fracture line to the physis and the maximum width of metaphyses from medial to lateral were measured, and the ratio between these were calculated to find out the most typical level of the DMRFOP in different-age patients (Figure 12).

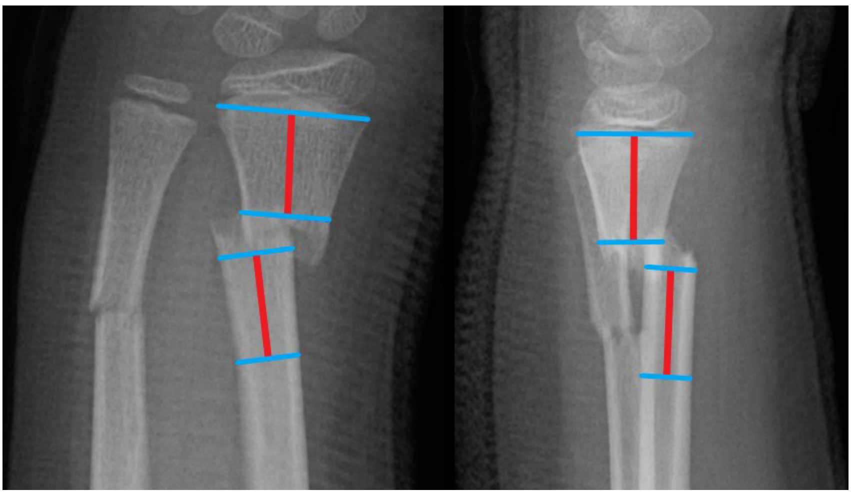
**Figure 12**

**Location of the fracture in the metaphysis is defined as a ratio between the shortest distance from the fracture to the distal physis (blue line, 17 mm) and the maximum width of the distal radial metaphysis (red line, 20 mm), which is 0.9 in this case (A).**

**In Study III,** all cast-treated patients (n=13) with DMRFOP during the study period were identified. One patient's guardian denied attending the clinical and the radiographic follow-up examinations. After that, 12 age-matched patients with a similar fracture pattern whose fractures were surgically fixed were identified from Kids' Fracture Tool. All 24 patients were invited to a radiographic and clinical follow-up appointment. Alignment of the fractures in the cast was assessed in radiographs of the 12 children, who were treated by casting their fractures in overriding position (Figure 13). Reduction and pin fixation were measured and registered in fluoroscopic images or radiographs taken after surgery.

**Figure 13**

**Angulation was recorded in frontal and sagittal planes by measuring the angle between the longitudinal axes (red lines).**



The eligibility criteria in the planned RCT (Study IV) will be children up to 10 years of age with DMRFOP and with open distal forearm physes. The children and their guardian need to be capable to communicate in Finnish, Swedish, or English. The exclusion criteria will be bilateral forearm fracture, Gustilo-Anderson grade I or III open fracture, Galeazzi fracture-dislocation, another acute fracture, polytrauma, neurovascular injury of the ipsilateral upper extremity, and history of a displaced forearm fracture or underlying disease affecting fracture healing. Participants' enrollment should be done within 72 hours after injury and definitive randomized treatment within 7 days (Table 6). All eligible but declined patients or guardians, as well as the noneligible patients and their guardians, will be asked if they accept to take part in the declined cohort of the study. The angulation of the radial fracture in AP- and lateral radiographs (Figure 12) will be measured at all follow-up points. The translation and shortening of the radial fracture will be measured at 1 week. The length of the radius will be measured at 4 weeks and every time point after that. Ulnar variance will be assessed by the method of Hafner (Kox 2020) (Figure 2) at 3 months follow-up and after that.

#### 4.1.2 TREATMENT

***Casting***

In studies I and III, a dorsal above-elbow and a volar below-elbow splint (DAE+VBE) was applied to all the patients, whose fractures were immobilized in an overriding position.

In Study IV, the DAE+VBE will be applied in finger-trap traction (Figure 14) in the casting group, but without finger-trap traction under general anesthesia after pin fixation in the surgery group. Immobilization will be 4 weeks in both groups. A dorsal below-elbow splint is applied for an additional 2 weeks if the fracture site is painful at 4 weeks.

***Pin fixation***

Pin fixation of DMRFOP was performed with 1–3 smooth pins in Study I, and with 1–2 smooth pins in Study III, respectively.

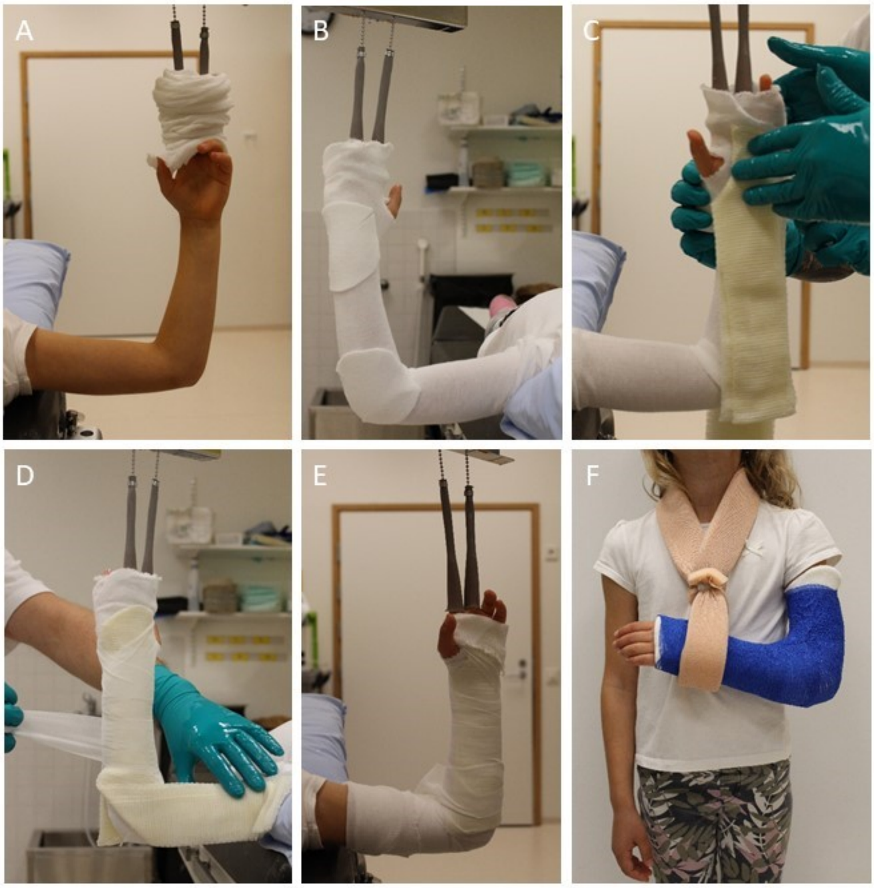
Reduction and osteosynthesis of DMRFOP in the surgery group in Study IV will be standardized. If reduction (less than 2 mm displacement and shortening, angulation <10° in any plane between fracture pieces) cannot be achieved after three closed attempts, it is performed through a 5 mm dorsal incision with a blunt dissector. Percutaneous pin fixation will be done with two 1.6 mm smooth pins. Both pins should gain purchase on both fracture fragments, and they should not cross at the level of the fracture. The number of unsuccessful attempts to place the pins, as well as the operation time, will be recorded. Stability of the pin fixation will be tested manually under a fluoroscopic image intensifier by placing the wrist in full extension and flexion while the forearm is kept in neutral rotation. The proximal ends of the pins should penetrate the radial cortex by 5 mm and their distal ends should be bent at a 90° angle approximately 1 cm from skin level and cut 10 mm from the bend.

***Flexible intramedullary nailing***

FIN was used to stabilize one patient's DMRFOP in Study I, and another patient's ulnar fracture whose DMRFOP was plated.

**Figure 14**

**The method used for making DAE+VBE.**
**A) Index and middle fingers are finger trapped.**
**B) Double stockinette is applied from fingers to axilla.**
**C-D) Synthetic volar below-elbow and dorsal above-elbow splints are tied in place with elastic bandage.**
**E) Splints are allowed to harden 5-10 minutes for the injured limb in finger-trap traction.**
**F) Final finish with colorful elastic bandage of patient's choice.**




### *Plate osteosynthesis*

Eleven patients' DMRFOP were plate fixed (four semitubular plates, four 3.5 mm locking plates, three anatomic distal radius plates) in Study I. Three of these patients' ulnar fractures were also plated.

### 4.1.3 FUNCTIONAL OUTCOME

***Study I***

Functional outcome was assessed by a telephone interview with patients' guardians at median 4.6 years (range 1.5–7.2) after the fracture.

***Study III***

A follow-up appointment for research purposes took place at mean 3.3 years (range 2.5–4.5 years) after the injury. Patients' photographs of both forearms were taken to assess symmetry, length, and forearm and wrist motion (Reddy 2005) (Figure 15). Forearm prosupination and wrist extension-flexion were measured from the photographs in degrees by three different members of the research team. The ratio between injured and uninjured sides were calculated from mean values of the measurements of prosupination, wrist extension-flexion, and radial-ulnar deviation. The grip strength of both hands was recorded by a Jamar® hydraulic dynamometer (Lafayette Instrument Company, Lafayette, IN, USA) as the best result of three attempts, and the ratio between injured and uninjured hands was then calculated.

**Figure 15**

**At the time of follow-up, this 9-year-old girl had sustained DMRFOP of her left radius with an associated greenstick-type fracture of her left ulna metaphysis at 5 years of age. Her fractures were treated by casting the radius fracture in overriding position.**

**A) forearms, anterior view**

**B) forearms, dorsal view**

**C) forearms, ulnar view**

**D) passive wrist flexion**

**E) passive wrist extension**

**F) active pronation**

**G) active supination**

**H) active ulnar deviation**

**I) active radial deviation**

### *Study IV*

Follow-up appointments and interventions are presented in Table 6. Active range of motion of the forearms and wrists will be assessed by photographs taken by a professional photographer, and passive extension of the wrists will also be evaluated from the photographs. The best of three photographs in all the positions will be used for the measurements. Active forearm prosupination will be registered by a wrist inclinometer (baseline measurement instrument) held by the patient during photography (Figure 16). The primary outcomes of the study are the ratios of forearm prosupination and wrist extension-flexion between the injured and uninjured sides. Length of both forearms will be measured from 3 months after treatment onward (Figure 16).

We will contact all patients at the age of 18 to assess the long-term effect of the fracture on the forearm and wrist function.

**Table 6**

**Schedule of interventions and assessments in the randomized controlled trial (Study IV).**

| **Timepoint** | **0–7 days** | **1 week** | **4 weeks** | **3 months** | **6 months** | **12 months** |
|---|---|---|---|---|---|---|
| Casting<br>(with finger-trap method) | x | | | | | |
| Reduction and pin fixation | x | | | | | |
| Removal of cast and splints | | | x | | | |
| Dorsal forearm splint<br>(for 2 weeks, if needed) | | | x | | | |
| ROM | | | x | x | x | x |
| Grip strength | | | x | x | x | x |
| QuickDASH | | | x | x | x | x |
| PedsQL | | x | x | x | x | x |
| Deformity measurements | | x | x | x | x | x |

**Figure 16**

**Photographs for evaluation of forearm motion, length, and shape. These measurements will be performed in the RCT trial at 4 weeks, at 3 and 6 months, and at 1 year. Pronation of the forearms (A-B). Supination of the forearms (C). Maximal active extension of the wrists (angle between red lines) (D-E). Maximal active flexion of the wrists (angle between red lines) (F-G). Shape of forearms in medial view (H-I). Maximal passive extension of the wrists (angle between red lines) (J). Length and shape of forearms dorsally (K-L).**

#### 4.1.4 OUTCOMES

***Study I***

One hundred (89%) guardians were contacted by telephone. Eleven guardians could not be reached (one pin fixation, three closed reduction and casting, one plating, one FIN), one patient had died.

Patients' guardians were asked if their child had pain during the last month in the injured forearm and to report its intensity from 0 (no pain) to 10 (worst possible pain). The function of forearm and wrist were registered as normal or abnormal, and possible forearm asymmetry was requested. More detailed questions were asked of guardians, who reported that their child had abnormal function of the injured upper limb or had forearm/wrist asymmetry. Subjective cosmetic outcome and satisfaction to treatment was also recorded, which was assessed by the 7-point Likert scale [ranging from 1 (totally unsatisfied) to 7 (totally satisfied)].

***Study III***

Patients and guardians were asked to answer the PedsQL Pediatric Pain Questionnaire (0–100 mm, 0 representing no pain and 100 mm worst imaginable pain) (Varni 1999), and the QuickDASH disability/symptom score questionnaire (0–100 points, 0 points representing no disability and no symptoms) (Beaton 2005). Patients who practiced sports were also asked to fill in the QuickDASH hobby module.

***Study IV***

Pain at rest and in activities experienced by the patients will be assessed with the PedsQL questionnaire at every follow-up.

Subjective patient-reported outcome is assessed with the QuickDASH questionnaire (11-item version of the disabilities of the arm, shoulder, and hand score) at every follow-up.

At the 6-month follow-up, the patient's guardians will be asked about their satisfaction with the given treatment. Satisfaction with the forearm function of the injured upper extremity and its effect on the patient's daily living, along with the satisfaction with the cosmetic outcome, are elicited using the following questions: "How satisfied are you with your child's affected arm in his/her daily life?" and "How satisfied are you with the cosmetic outcome of your child's arm?" (5-step Likert scale). In addition, the overall satisfaction with the treatment is assessed with the question, "How satisfied are you with the overall treatment your child had?" (5-step Likert scale).

### 4.1.5 ADVERSE EVENTS

***Study I and III***

All adverse events were recorded from the patients' files.

***Study IV***

In the RCT, the possible adverse events will be categorized as serious adverse events (SAEs) and minor adverse events (MAEs). Complications such as iatrogenic permanent nerve injury, deep infection of the fracture site, and systemic infections will be categorized as SAEs. MAEs will include, but are not limited to, cast sore, superficial infection, nonunion (clinically unstable fracture at 3 months), refracture, pin loosening, transient nerve injury, or tendon injury.

## 4.2 STUDY II

In the survey, we presented radiographs (anteroposterior and lateral view) of three different DMRFOP with varying types of distal ulna fractures (Figure 17) in 5- to 7-year-old children. The website SurveyMonkey™ (San Mateo, California, USA) was used as a platform for the survey. With an iPad, we collected the answers of 49 orthopedic surgeons, who were asked to participate in the survey, at the European Pediatric Orthopedic Society (EPOS) meeting in Tel Aviv, Israel. Only one surgeon refused to answer the survey.

Furthermore, we sent the link to the query by e-mail to several pediatric orthopedists in the most prominent pediatric hospitals in Europe, the United States of America, and Australia, getting 165 responses. Altogether, 213 surgeons from different countries participated in the survey (Table 8). The response rate to the e-mailed queries is unknown, because respondents were asked to forward the questionnaire link to their colleagues who treat children's fractures.

In the survey, the respondents were asked about the length of their experience in pediatric fracture treatment. Roughly one-third (36%) of the respondents claimed to have more than 10 years of experience (Table 8).

Respondents were asked to choose their preferred treatment method, type, and length of immobilization, as well as the number of radiological and clinical follow-ups, using multiple- choice questions (Table 7).

**Figure 17**

**A** **Case 1: 5-year-old child with DMRFOP and nondisplaced, slightly angulated ulna fracture.**

**B** **Case 2: 7-year-old child with DMRFOP and sub-totally displaced and angulated ulna fracture.**

**C** **Case 3: 5-year-old child with DMRFOP and completely displaced ulna fracture.**

**Table 7**

**Questions and answer options in the survey.**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Method of treatment** | Cast immobilization without reduction | Alignment adjustment during casting | Reduction in local anesthesia | Reduction under anesthesia | Percutaneous pin fixation | Open reduction and pin fixation | Plate fixation |
| **Type of cast** | None | Dorsal forearm splint | Dorsal and volar forearm splint | Above-elbow dorsal splint | Above-elbow dorsal and volar forearm splint | Circular forearm cast | Circular above-elbow cast |
| **Length of immobilization (weeks)** | none | 1 | 2 | 3 | 4 | 5 | 6 |
| **Number of radiological follow-ups** | none | 1 | 2 | 3 | 4 | 5 | 6 |
| **Number of clinical follow-ups** | none | 1 | 2 | 3 | 4 | 5 | 6 |

**Table 8**

**Respondents' length of experience in children's fracture treatment and their country of employment.**

| | | n | % |
|---|---|---|---|
| **Experience** | <1 year | 47 | 22 |
| | 1-5 years | 56 | 26 |
| | 6-10 years | 34 | 16 |
| | >10 years | 76 | 36 |
| | **Total** | **213** | **100** |
| **Country** | Finland | 73 | 34 |
| | USA | 50 | 23 |
| | Sweden | 14 | 7 |
| | Australia | 9 | 4 |
| | Austria | 7 | 3 |
| | UK | 7 | 3 |
| | Estonia | 6 | 3 |
| | Norway | 6 | 3 |
| | France | 5 | 2 |
| | Russia | 5 | 2 |
| | Switzerland | 5 | 2 |
| | Germany | 4 | 2 |
| | Israel | 4 | 2 |
| | China | 3 | 1 |
| | Netherlands | 2 | 1 |
| | Portugal | 2 | 1 |
| | Ukraine | 2 | 1 |
| | Armenia | 1 | <1 |
| | Denmark | 1 | <1 |
| | Italy | 1 | <1 |
| | Japan | 1 | <1 |
| | Mexico | 1 | <1 |
| | Northern Ireland | 1 | <1 |
| | Romania | 1 | <1 |
| | Singapore | 1 | <1 |
| | Turkey | 1 | <1 |
| | **Total** | **213** | **100** |

## 4.3 ETHICS AND SAFETY FACTORS

Helsinki University Hospital's Review Board approved the study protocols:

Study I-III 365/13/03/03/2015

Study IV HUS/2345/2019

Study IV was also registered at ClinicalTrials.gov (NCT04323410) before the commencement of recruiting

### *Study IV*

#### Data Safety and Monitoring committee

Safety factors of the study will be taken into account by the Data Safety and Monitoring Committee (DSMC). The members of DSMC are independent specialists, and they will be convened to monitor adverse events (AEs) in order to ensure the safety of participating patients. The DSMC will evaluate the patients' data two times: first, when twenty and second, when forty patients have been recruited. The DSMC will have access to unblinded data as well as radio- and photographs. The committee evaluates adverse event severity, and based on their determinations, authorizes researchers to continue the RCT if possible. If the DSMC considers ending the RCT, they will consult the institutional review board.

Members of the DSMC will not be involved in the RCT, nor will they have any conflict of interest nor benefit from the results of the RCT.

#### Recruiting doctor

In the study the recruiting doctor will obtain the informed consent. The consent form is filled out by the patient's guardian, and the consent papers will be carefully maintained in the researchers' locker in the New Children's Hospital office on the third floor. Databases will be maintained in secure storage at the research center for 15 years after completion of the study. Every file that contains individual data will be secured by password.

#### Participants and guardians

Eligible RCT patients and their guardians will be carefully informed before their possible consent. They will also have enough time to consider their consent about the patients' participation in the RCT. They also will be informed that refusing will not influence the quality of their fracture treatment. Participants and/or their guardians can also stop their involvement at any time by informing the researchers. Patients and their guardians will not receive any compensation for any harms from the treatment.

Change in the treatment regimen

If at any point during the RCT an imminent or unexpected adverse events occurs, the treating consultant surgeon can change the treatment regimen, if necessary, for the safety of the patient.

## 4.4 STATISTICAL METHODS

All analyses were performed using SPSS for Windows (IBM Statistics for Windows, Version 22.0, released 2013, IBM Corp, Armonk, NY, USA). Significance was set at 0.05 and in Study II Cronbach's α with a cut-off value of 0.8.

***Study I***

The Poisson distribution was utilized to calculate the 95% confidence intervals (CIs) for the incidences. Results were presented as the median for non-normally distributed variables and as the mean ± standard deviation for continuous, normally distributed variables. The frequency distribution was compared between groups with use of the chi-square test for categorical variables and the Mann-Whitney U test for continuous variables.

***Study II***

The response distribution for each individual question was registered, and the agreement between surgeons was determined using Cronbach's α. Binary logistic regression analysis was performed to determine which parameter (ulnar fracture type, surgeon's experience in pediatric orthopedics, country of origin) was the most significant predictor for osteosynthesis. Comparison between countries was done only between Nordic countries (Finland, Denmark, Norway, and Sweden) and the USA due to the small number of respondents from other countries. Demographic data were explored using a chi-square test and Pearson's correlation

***Study III***

There was no statistical analysis in the study.

***Study IV***

All analyses will be performed on the intention-to-treat principle, where the participants are analyzed in their allocated treatment groups regardless of the received treatment. The descriptive statistics will be presented as means with SDs, as medians with IQR or as counts with percentages. The groups will be compared with the t-test, for continuous variables, and Pearson's $\chi 2$ test or Fisher's exact test, for categorical variables. The primary treatment effect will be quantified with the difference between the groups in ROM ratio (pro-supination of the forearm and flexion–extension of the wrist) with the associated 95% CIs at 6 months post-randomization. Repeated measurement results will be compared between groups with mixed effect models and an unstructured covariance structure (i.e., the Kenward-Roger method for calculating degrees of freedom). We consider fixed effects to include group, time, and group-time interactions. Mixed models allow the analysis of unbalanced data sets without imputation; therefore, all available data will be analyzed using a complete set of analyses. The AEs of the study arms will be reported descriptively.

# 5 RESULTS

## 5.1 EPIDEMIOLOGY (I)

We treated 112 children and adolescents under 16 years of age with altogether 113 DMRFOPs in Children's Hospital (now New Children's Hospital, Helsinki) during the study period between 2014 and 2019. Of these 112 patients, 81 were citizens of Helsinki. The number of children who had sustained a DMRFOP varied between 7 and 18 per year. The calculated mean incidence during the 6-year study period was 1.42/10,000/year (range 0.72–2.01). More detailed information is presented in Table 9.

**Table 9**

**The number of boys and girls in the census population in Helsinki; the number and the annual incidence of distal metaphyseal radial fractures in overriding position (DMRFOP).**

| Year | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | Total / mean |
|---|---|---|---|---|---|---|---|
| **Children aged 0–15 years (n)** | 91,002 | 93,054 | 94,606 | 96,716 | 98,052 | 98,938 | **572,368** |
| Male | 46,460 | 47,639 | 48,482 | 49,533 | 50,094 | 50,571 | **292,779** |
| Female | 44,542 | 45,415 | 46,124 | 47,183 | 47,958 | 48,367 | **279,589** |
| **Number of DMRFOP** | 10 | 18 | 19 | 7 | 14 | 13 | **81** |
| Male | 4 | 8 | 17 | 4 | 8 | 8 | **49** |
| Female | 6 | 10 | 2 | 3 | 6 | 5 | **32** |
| **Incidence per 10,000/year, (95% CI)** | **1.1** | **1.93** | **2.01** | **0.72** | **1.43** | **1.31** | **1.42 (0.90–1.94)** |
| Male | 0.86 | 1.68 | 3.51 | 0.81 | 1.60 | 1.58 | **1.67** |
| Female | 1.35 | 2.20 | 0.43 | 0.64 | 1.25 | 1.03 | **1.15** |

Seasonal variation in incidence of DMRFOP was similar to all children's fractures (Figure 18). Nearly half (49%) of the children and adolescents that had sustained a DMRFOP had fallen from high. The second most common injury mechanism was a fall during sports (organized 23%, unorganized 19% (Figure 19). The risk of sustaining DMRFOP is higher in children than in adolescents (Table 5 and Figure 20).

**Figure 18**

**Monthly incidence of DMRFOP (n=112) during the study period 2014–2019**

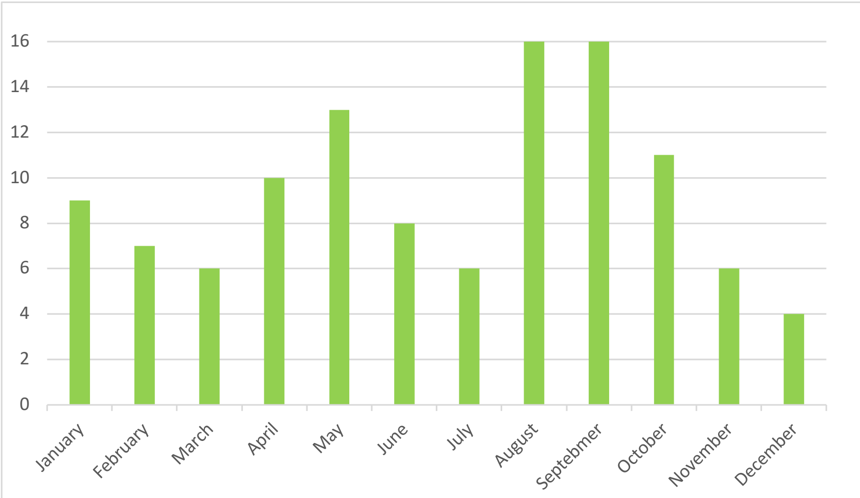



**Figure 19**

**Patients' Injury mechanisms (n) during study period**

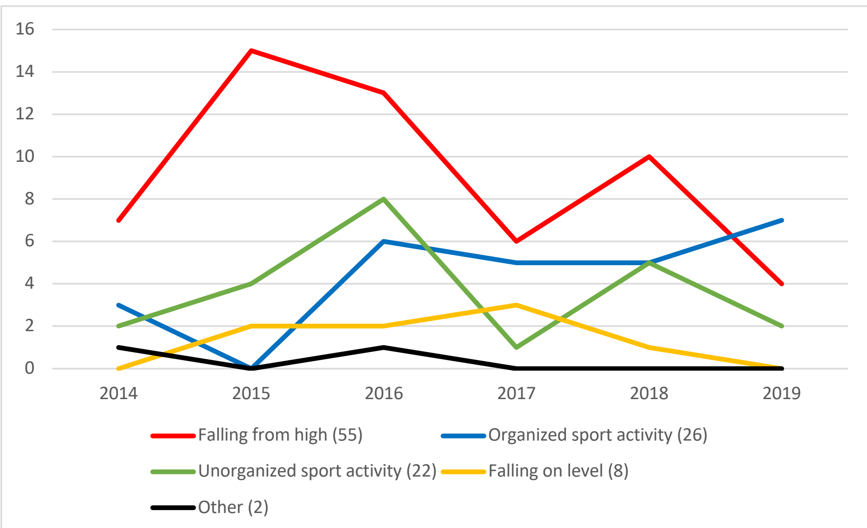
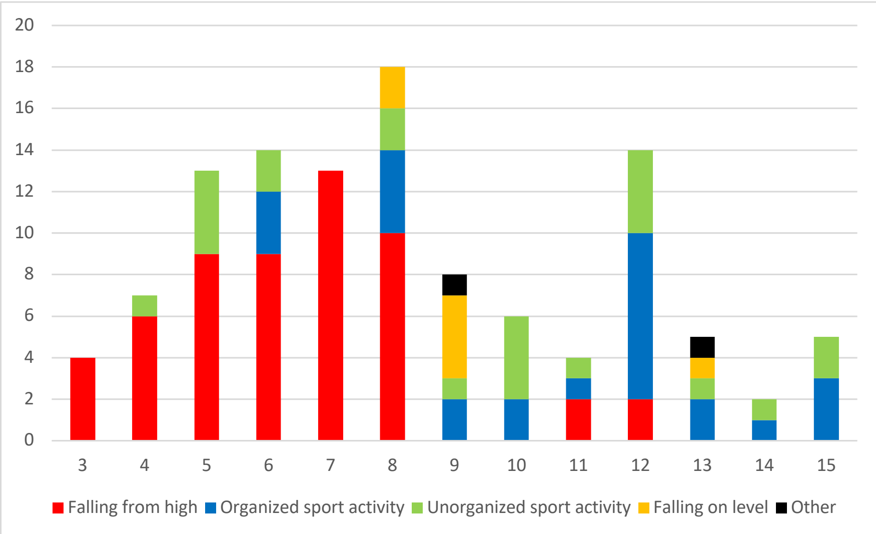


**Figure 20**

**Injury mechanisms at different ages of DMRFOP patients**




## 5.2 MORPHOLOGY OF DMRFOP (I)

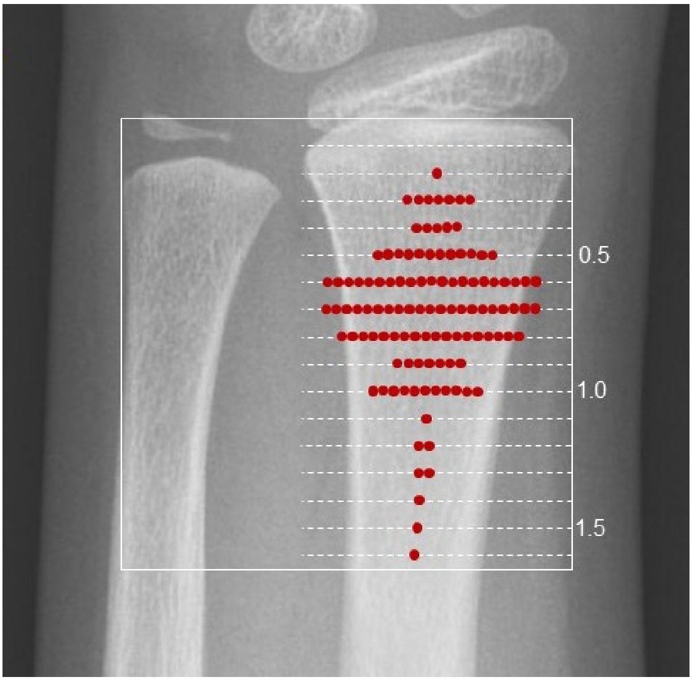
Most (104/113, 92%) DMRFOP were horizontally oriented fractures, and the distal fracture fragment was displaced dorsally in 105 cases (93%). Some radial displacement was also evident in 75/113 cases. Volar displacement of the distal fracture fragment was seen in 8 children.

All except one patient had also a radiologically evident fracture in the distal ulna (greenstick 41, torus 28, overriding 27, complete 8, avulsion of styloid process 4, epiphyseal 4 [Peterson I 2, II 1, III 1]).

Fracture level of DMRFOP varied, although there was a clear tendency of the fracture to occur at a certain level (Figure 21).

**Figure 21**

**The level (red dots) of DMRFOP (n=113).**




## 5.3 CURRENT TREATMENT (I–III)

### 5.3.1 STUDY I

#### *First aid*

There were 113 DMRFOPs in 112 patients during the study period 2014–19. Most of these patients arrived directly to our hospital (71%) by a private motor vehicle. The rest of the patients were first assessed in a private clinic (13%), local hospital (9%) or healthcare center (9%). One-third of the patients (32%) were transported by ambulance directly to our institution from the accident scene. Paramedics had splinted 25/36 children's fractures before or during the ambulance transport.

#### *Primary care*

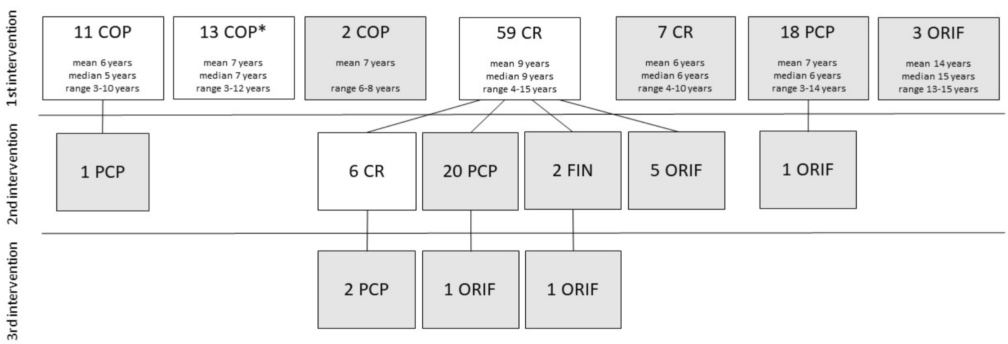
Closed manipulation of the fracture was performed in 72 cases (64%), 59 in the ED and 13 in the operation room (OR). Eighteen fractures were pin fixed, and three fractures were plated. The method of primary intervention was decided by the resident in 64 cases and by the attending surgeon in 49 (Figure 22).

### *Secondary interventions*

Closed manipulation in the ED failed in 33 patients (46%), and an additional 13 patients had a secondary intervention because their fracture alignment worsened during follow-up. Twenty of these 46 patients' fractures were reduced, and pin fixed, 13 were left in an overriding position in the primary cast, six re-reduced in the ED, five were plated and two were fixed with FIN. One child's pin-fixed fracture lost satisfactory alignment after early pin removal at 3 weeks and was then plated. Four patients had three interventions (Figure 22).

**Figure 22**

**Implementation of treatment in 113 DMRFOPs in the hospital for children and adolescents and New Children's Hospital (Helsinki) during 2014–19. Treatment in ED (white boxes) and in OR (gray boxes).**
**COP, cast immobilization in overriding position; CR, closed reduction; PCP, percutaneous pin fixation; ORIF, open reduction and internal fixation with a plate; FIN, flexible intramedullary nailing.**



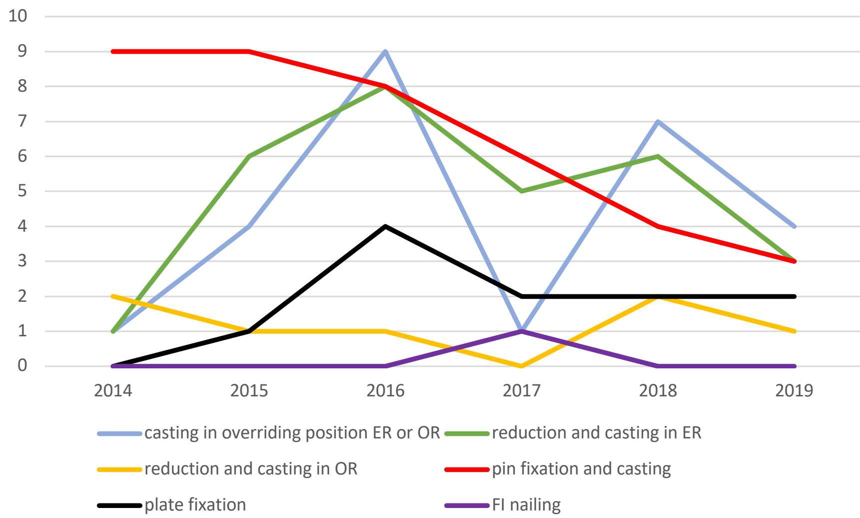

*Failed attempt at closed reduction in ER.

### *Definitive treatment*

Altogether 25 (22%) DMRFOPs were treated by casting without reduction of the fracture. Reduction and casting was the definitive treatment in 37 fractures (33%), pin fixation in 39 (35%), plate fixation in 11 (10%) and FIN in 1 fracture. The rate of pin fixation has decreased, whereas casting in overriding position in the ED has increased during the study period (Table 23).

**Figure 23**

**Definitive treatment methods on 113 DMRFOPs in the study period.**




## *Hospital care and follow-up*

Operatively treated patients had a longer hospital stay than children treated in the ED. Unscheduled returns to ED happened in ten operatively (total n=50, 20%) treated and in four non-operatively (total n=62, 6.5%) treated patients. Operatively treated children had eight mid- or long-term visits whereas non-operatively treated had 13 (Table 10).

**Table 10**

**Patients (n=112) all visits and follow-up controls during study period at the hospital.**

| Definitive treatment | | Visits to ED | Days at ward | Unexpected visits to ED | Follow-up controls | Mid-/long-term follow-up controls |
|---|---|---|---|---|---|---|
| **Cast treated (n=26)** | range | 0–2 | 0–2 | 0–2 | 0–3 | 0–2 |
| | mean | 1 | 0.2 | 0.1 | 1.8 | 0.4 |
| | median | 1 | 0 | 0 | 2 | 0 |
| **Reducted (n= 36)** | range | 0–2 | 0–2 | 0–2 | 1–3 | 0–1 |
| | mean | 1 | 0.3 | 0.1 | 1.8 | 0.1 |
| | median | 1 | 0 | 0 | 2 | 0 |
| **Pin fixed (n=38)** | range | 0–1 | 0–3 | 0–2 | 1–4 | 0–2 |
| | mean | 1 | 1.7 | 0.2 | 1.5 | 0.1 |
| | median | 1 | 2 | 0 | 1 | 0 |
| **Plate fixed (n=11)** | range | 1 | 1–4 | 0–3 | 1–4 | 0–2 |
| | mean | 1 | 2.3 | 0.5 | 1.7 | 0.2 |
| | median | 1 | 2 | 0 | 2 | 0 |
| **FI-nailed (n=1)** | | 1 | 4 | 0 | 2 | 0 |

### *Pain medication*

Paramedics set an intravenous cannula to 18 patients (n=36) during the ambulance transfer. Strong opioids were administered to 25 patients (fentanyl 22, morphine 3).

Information about the pain medication administered during fracture treatment was available in 93 of the 112 patients' records. Strong opioids were given to 70 of these 93 (75%) patients. All patients who had treatment in the OR (n=59) were given strong opioids, whereas 15 of the 72 patients (21%) who had manipulation of their fractures in the ED were medicated with strong opioids in addition to local anesthesia and/or nitrous oxide.

Records of pain medicine prescription at discharge of 81/112 patients were found, according to which the most popularly (70% of all prescriptions) prescribed medication was a combination of acetaminophen with ibuprofen. Tramadol prescriptions were given to 13/81 (16%) patients.

### *Immobilization*

Four different types of splints were used in treatment of DMRFOP in our institution during the study period (Table 11).

**Table 11**

**Different types of splints and the length of immobilization (weeks) after primary treatment of DMRFOP.**

| Immobilization after primary treatment | Dorsal forearm splint | Dorsal above-elbow splint | Dorsal and volar forearm splint | Above-elbow dorsal and volar splint | No immobilization | Length of immobilization mean (range) |
|---|---|---|---|---|---|---|
| Cast immobilization without reduction | - | 3 | 1 | 22 | - | **4.2 (4–5)** |
| Reduction in ED | 4 | 5 | 14 | 36 | - | **4.2 (4–5)** |
| Reduction in OR | - | 4 | - | 3 | - | **4** |
| Percutaneous pin fixation | 4 | 8 | - | 6 | - | **4.5 (3–9)** |
| Plate fixation | 2 | - | - | - | 1 | **3.3 (0–6)** |
| **Total (n=113)** | **10** | **20** | **15** | **67** | **1** | |
| **Length of immobilization mean (range)** | **4.09 (4–6)** | **4.23 (3–9)** | **4** | **4.31 (4–9)** | **0** | |

### *Satisfaction and mid-/long-term follow-up.*

Six guardians reported transient pain (median 2.7, range 2–7) in their child's injured forearm during or after heavy activities. Four of these six children's fractures had been fixed (pins 3, plate 1) and two had been treated by closed reduction and casting.

Forearm asymmetry was reported by eleven guardians. Three of these patients had been treated by casting without reduction, four with reduction and casting and four were pin fixed. Nine of the eleven guardians estimated their child's forearm asymmetry to be so minor that they refused to attend further follow-up appointments.

Abnormal forearm and/or wrist function was reported by four guardians in heavy upper limb activities. Three of these patients' fractures had been fixed with pin fixation, and one child's fracture had been reduced and cast.

Dissatisfaction with the cosmetic outcome of the treatment was reported by seven guardians, who all complained of ugly forearm scars from plate osteosynthesis (3), pin fixation (3) or a cast applied after reduction of the fracture (1).

Most (91%) of the guardians were satisfied with their child's treatment (mean 6.2, median 7, range 1–7). Six guardians gave < 3 points for treatment: three of them reported pain during a failed closed reduction attempt, one guardian complained about pin removal without general anesthesia, one was dissatisfied with a visible malunion of their child's reduced fracture after cast removal, and one reported dysfunction of the child's injured limb after cast immobilization without reduction. Four guardians also reported that they would have been more satisfied with the treatment if the waiting time had been shorter, especially in the ED.

### *Adverse events*

Pressure sores were registered in two children: one from a cast applied after closed reduction and another one from a Jurgan pin ball left under the cast.

Superficial pin site infections were healed by local treatment and oral antibiotics in two patients.

Transient sensory symptoms of the median nerve resolved during cast immobilization in two patients. No fracture or treatment-related permanent nerve injuries were encountered.

Malunion of DMRFOP was evident in ten patients (closed reduction and casting 6, pin fixation 3, FIN 1). Two of these patients had a correction osteotomy and plate fixation.

DRUJ instability was diagnosed in a 14-year-old boy 2 years after treatment of his DMRFOP with a torus fracture of the distal ulna with closed reduction and casting, which healed into 18° apex dorsal- and 15° apex radial angulation. Malunion of his radius had partially remodeled at 6 months' follow-up, when 8° dorsal- and 9° radial angulation were measured from radiographs. He was treated by corrective osteotomy of the radius, which stabilized his DRUJ.

### *Quality of the treatment*

#### Cast immobilization in an overriding position

Twenty-six patients' DMRFOP were immobilized without reduction (13) or after a failed reduction attempt (13). One 4-year-old boy had his DMRFOP pin fixed a week later, because the attending surgeon, who primarily accepted casting the fracture in an overriding position, changed his mind.

A slightly visible forearm deformity (20° curvature of ulna in radiographs) was recorded in an 8-year-old boy 3 years after sustaining a DMRFOP with an associated completely displaced ulna fracture. Both fractures had a clear angulation in the cast with up to 29° of apex radial angulation in the ulna. He had a 30° deficit of supination, without symptoms (Table 15, Case 2).

#### Reduction and cast immobilization

Reduction of DMRFOP in the ED failed in 46% (33/72) cases, performed by a resident (24/55), attending surgeon (9/17). Overriding position in the cast was accepted by the attending surgeon in 13 cases. Six fractures were re-reduced in the ED, 20 were pin fixed, five plated and two treated with FIN. The mean accepted dorsal angulation was 14° (range 0°–33°), radial 12° (0°–29°), respectively and the median accepted displacement ratio after reduction 23% (0–61%).

Fixation

Pin fixation was performed in 41 cases, in 18 patients as the primary treatment. Fracture alignment was partially lost in two pin-fixed patients, whose fractures were then plated. One pin was used in 13, two in 27 and three in 1 case. Pin fixation was technically unsatisfactorily performed in one case with no pins purchasing both fracture fragments. The mean accepted dorsal angulation was 5° (range 0°–30°) and radial angulation 5° (0°–26°). The median accepted displacement ratio after pin fixation was 14% (0–50%). Angulation exceeded 10° or displacement over 20% in 19 of the 41 pin-fixed cases.

Eleven patients' fractures were plated, all into satisfactory alignment (< 5° angulation, 0–1 mm of displacement).

FIN was performed in two patients by the same surgeon. A clear displacement (33% and 57%) in the radial fracture was evident post-operatively. Both nails were removed, at 3 and 7 weeks from the fracture. Malunion developed in both cases, of which one was corrected by osteotomy.

### 5.3.2 STUDY II

#### *Treatment methods*

Case 1

In the first presented case scenario (Figure 17, A) 51% of the respondents chose reduction and casting, 31% pin fixation and 18% casting without anatomic reduction.

Case 2

In the second presented case scenario (Figure 17, B) 46% of the respondents preferred reduction and casting, 46% pin fixation and 8% casting without anatomic reduction.

Case 3

In the third presented case scenario (Figure 17, C) 49% of the respondents fancied pin fixation, 33% reduction and casting, 18% casting without anatomic reduction.

Four respondents (2%) chose to treat all three cases without anatomic reduction, whereas 176 (83%) would have reduced all three presented fractures. Nearly all (99%) of the surgeons who would reduce and fix the presented fractures would have used pins for internal fixation (Figure 17).

### *Immobilization*

There was no consensus about the preferred type of cast or splint in any of the presented cases (Table 12).

The most popular (28%) method of immobilization was an above-elbow dorsal and volar splint, followed by a circular below-elbow cast (27%) and above-elbow circular cast (23%) (Table 13).

The preferred length of immobilization varied between 0 and >6 weeks: no immobilization 0.8%, 2 weeks 1.4%, 3 weeks 12.8%, 4 weeks 43.8%, 5 weeks 13.9%, 6 weeks 26.4%, and >6 weeks 0.8%.

Nordic surgeons appear to prefer pin fixation compared with American surgeons (54% vs. 31%, $p<0.001$), above-elbow splints and 4 weeks immobilization, whereas Americans seem to advocate reduction without internal fixation (69%) and circular below-elbow casts for 6 weeks.

**Table 12**

**All 639 chosen treatment methods for the three presented cases in the survey.**

| | | Case 1 | Case 2 | Case 3 | Total |
|---|---|---|---|---|---|
| No reduction | Cast immobilization without reduction | 22 | 10 | 20 | 52 |
| | Alignment adjustment during casting | 17 | 7 | 19 | 43 |
| | Total | 39 | 17 | 39 | **95** |
| Reduction | Reduction in local anesthesia | 16 | 6 | 28 | 50 |
| | Reduction under anesthesia | 93 | 93 | 42 | 228 |
| | Total | 109 | 99 | 70 | **278** |
| Reduction and osteosynthesis | Percutaneous pin fixation | 58 | 86 | 49 | 193 |
| | Open reduction and pin fixation | 6 | 10 | 55 | 71 |
| | Plate fixation | 1 | 1 | 0 | 2 |
| | Total | 65 | 97 | 104 | **266** |

**Table 13**

**Chosen splint- and cast types in the three presented case scenarios in the survey**

| | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| No immobilization | 2 | 3 | 0 |
| Dorsal forearm splint | 20 | 20 | 10 |
| Dorsal and volar forearm splint | 20 | 19 | 7 |
| Dorsal above-elbow splint | 9 | 28 | 7 |
| Above-elbow dorsal and volar splint | 43 | 43 | 93 |
| Forearm cast | 41 | 44 | 86 |
| Above-elbow cast | 78 | 56 | 10 |
| Total | 213 | 213 | 213 |

### *Radiological and clinical follow-up*

There was a large variation in the recommended number of follow-up radiographs and visits.

From those who chose casting without reduction as a method of treatment, 77% would like to schedule follow-up radiographs at 1, 38% at 2 and 57% at 4 weeks from the injury. Thirteen percent of all recommended radiographic controls would be taken between 3 and 12 months after injury and 6% after 1 year.

Surgeons who preferred reduction and cast immobilization without internal fixation would arrange radiographic follow-up at 1 (74%), 2 (43%) and 4 (46%) weeks from the injury. Some (2%) surgeons would like to take x-rays also at 1 year from the fracture.

Surgeons who would fix the presented fractures internally would schedule radiographic control at 1 (62%), 2 (31%) and 4 (48%) weeks after surgery.

There was no consensus about the clinical follow-up schedule either and the recommendation did not correlate to preferred treatment method. Most surgeons would arrange 2–4 follow-up appointments (Table 14)

**Table 14**

**The total number and percentage of chosen mid-term follow-up visits after different chosen treatment methods.**

| Follow-up time-point | Casting (n=95) | | Reduction (n=278) | | Fixation (n=266) | |
|---|---|---|---|---|---|---|
| 6 months | 12 | 15% | 41 | 15% | 31 | 11% |
| 12 months | 29 | 37% | 48 | 17% | 41 | 15% |
| 18 months | 2 | 3% | 0 | 0% | 6 | 2% |
| 24 months | 2 | 3% | 9 | 3% | 12 | 4% |
| > 2 years | 2 | 3% | 5 | 2% | 2 | 1% |

### 5.3.3 STUDY III

***Deformity and length of the forearms***

None of the patients had remarkable visible deformities except one minimally curved forearm in the patient with curved ulna and straight radius, described earlier (Table 15, Case 2). None of the patients or guardians reported forearm length discrepancies at the mid-term follow-up, but the injured forearm was minimally shorter in the photographs of the nine cast-treated and two operated patients. One of these patients is in Figure 15, and the minimal length discrepancy of the forearms and hand is seen in photograph C. Six reduced and fixed forearms of the patients were minimally longer than the uninjured site. Altogether six patients' forearms were equally long in the photographs (three cast and three reduced and fixed).

***ROM and grip strengths***

Forearm and wrist ROM and grip strength ratios have been described patient by patient in Table 15. The differences in the measured ranges of motion between the patients were unremarkable. The grip strengths were equal or better in the dominant hand in all patients, even if one patient had a right index finger fracture 3 weeks before the time of measurements.

***Radiological measurements***

The mean angulation of the DMRFOP in the cast-treated group was 7.9° (range 0°–16°) and shortening 6.6 mm (range 2–12 mm). In the patients whose fractures were pin fixed, the mean angulation in the fluoroscopic pictures was 1.9° (range 0°–9°), and there was no measurable shortening in any patients.

In five cast-treated and three pin-fixed patients, there was measurable angulation in the plain radiographs at the time of mid-term follow-up. The maximal angulation was 5° in one patient in both treatment groups. Those patients' radiographs are presented in Figure 24. All other patients' fractured forearms were healed and remodeled well.

Ten patients' fractures were fixed with two pins and two with one pin. Two pins were set crossed in nine times and one time they were in parallel position. One fracture was fixed in one intramedullary positioned in a proximal fragment. All other pins had purchase on both fragments of the fractures.

### *Patient-reported outcomes*

In the PedsQL and QuickDASH questionnaires, 23 patients (n=24) reported no pain nor any kind of disability/difficulties with their injured forearm. One (Table 15, Case 19) patient reported mild pain (21 mm, scale 0–100 mm) in PedsQL six years and 10 months after the injury. Her fracture was treated by reduction and pin fixation and there was no measurable deformity in her injured forearm's radiographs at the mid-term follow-up. She also scored 4.5 points (scale, 0–100 points) in QuickDASH. All the patients reported that they had returned to their normal daily lives, and they had participated in all sports activities.

All of 24 patients' guardians responded "yes" at the mid-term follow-up to the question "Would you choose the same definitive treatment method for your child if he/she had the same kind of distal forearm fracture now?"

### *Adverse events*

In Study III two operatively treated patients had complications. One patient had a superficial pin site infection which was treated by per oral antibiotics. Another patient's fracture alignment was lost after pin removal and malunited in dorsal 35° angulation. Five weeks after pin removal, the malunion was treated by correction osteotomy and plate (Figure 22).

**Table 15**

**Demographics, fracture type of the associated ipsilateral ulna fracture, and forearm and wrist function ratio[1] in 24 children in Study III.**

**Immobilized in overriding position**

| case number | age (years) | gender | injured side[2] | ulna fracture type | length of immobilization[3] | pronation | supination | Extension | flexion | wrist movement in coronal plane | grip strength |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.8 | boy | left | greenstick | 30 | 0.98 | 1.13 | 1.03 | 0.99 | 1.4 | 1 |
| 2 | 5.1 | boy | left | overriding | 29 | 1 | 0.91 | 0.94 | 1.02 | 0.84 | 0.88 |
| 3 | 5.4 | girl | left | greenstick | 31 | 1.07 | 0.83 | 1.08 | 1.1 | 1.4 | 0.88 |
| 4 | 5.8 | boy | **right** | torus | 30 | 0.85 | 0.88 | 1.08 | 0.97 | 0.93 | 1 |
| 5 | 5.9 | girl | left | torus | 24 | na | na | na | na | na | na |
| 6 | 6.8 | girl | left | greenstick | 32 | 0.96 | 1.06 | 1.02 | 0.8 | 0.95 | 0.95 |
| 7 | 6.9 | boy | left | greenstick | 24 | 1 | 0.96 | 0.97 | 1.07 | 1.07 | 1 |
| 8 | 7.3 | boy | **right** | greenstick | 28 | 0.98 | 1.01 | 0.95 | 0.96 | 1.13 | 1 |
| 9 | 7.4 | girl | left | Peterson I | 28 | 0.84 | 1 | 0.98 | 0.89 | 1.04 | 1 |
| 10 | 8.6 | boy | left | greenstick | 24 | 0.97 | 0.97 | 1.13 | 1.04 | 1.11 | 1 |
| 11 | 8.6 | boy | left | overriding | 29 | 1.34 | 1.17 | 1.04 | 1.04 | 1.13 | 1.24 |
| 12 | 9.9 | boy | left | greenstick | 38 | 1 | 0.95 | 0.96 | 0.9 | 0.85 | 0.93 |
| | | | | **mean** | **28.9** | **1** | **0.99** | **1.02** | **0.98** | **1.08** | **0.99** |
| | | | | **median** | **29** | **0.98** | **0.97** | **1.02** | **0.99** | **1.04** | **1** |
| | | | | **range** | **24–38** | **0.85–1.34** | **0.83–1.17** | **0.94–1.13** | **0.8–1.07** | **0.8–1.4** | **0.88–1.24** |

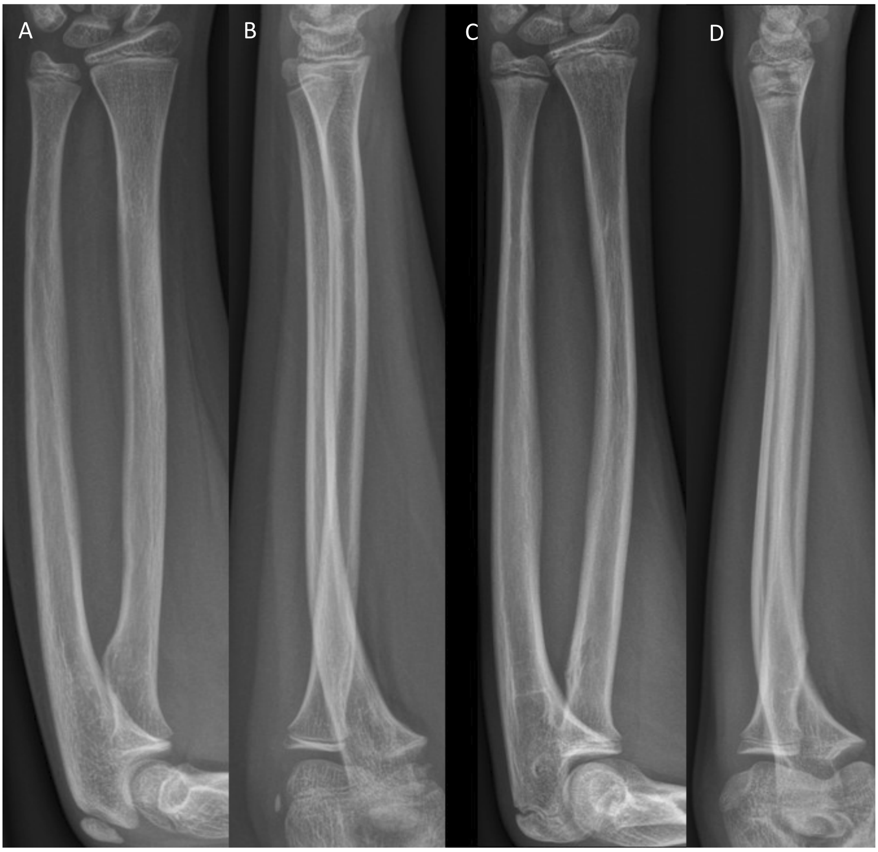
## Reduced and pin fixed

| case number | age (years) | gender | injured side[2] | ulna fracture type | length of immobilization[3] | pronation | supination | extension | flexion | wrist movement in coronal plane | grip strength |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 5 | girl | left | torus | 27 (27) | 1.05 | 1.08 | 1.01 | 0.87 | 0.81 | 0.7 |
| 14 | 5.3 | boy[4] | left | overriding | 21 (21) | 1.01 | 0.95 | 1.03 | 1.03 | 0.93 | 1 |
| 15 | 5.8 | boy | **right** | greenstick | 25 (24) | 0.99 | 0.98 | 1 | 0.94 | 1.11 | 1.14 |
| 16 | 6.2 | boy | **right** | greenstick | 32 (31) | 1.02 | 0.96 | 0.79 | 0.89 | 0.96 | 1.64 |
| 17 | 6.3 | boy | **right** | torus | 32 (31) | 0.84 | 1.07 | 0.87 | 1.21 | 1.41 | 1.06 |
| 18 | 6.8 | boy | **left** | no | 33 (31) | 1.06 | 1.13 | 1.11 | 1.02 | 1.03 | 1.13 |
| 19 | 6.8 | girl | left | overriding | 36 (36) | 0.91 | 1.02 | 1.06 | 0.94 | 1.17 | 0.89 |
| 20 | 7.3 | girl | left | overriding | 30 (30) | 0.94 | 1.05 | 1 | 0.99 | 1.02 | 1 |
| 21 | 7.8 | boy | **right** | overriding | 22 (21) | 0.85 | 0.98 | 1.12 | 0.95 | 0.98 | 1.06 |
| 22 | 8.3 | boy | **right** | torus | 32 (32) | 1 | 1.01 | 0.95 | 0.99 | 1.2 | 1 |
| 23 | 8.9 | boy | left | overriding | 34 (32) | 1.09 | 0.98 | 1 | 1.07 | 0.97 | 0.61 |
| 24 | 9.3 | boy | **right** | no | 45 (35) | 1.02 | 0.82 | 1.08 | 1.01 | 0.95 | 1.17 |
| | | | | **mean** | **30.8 (39.3)** | **0.98** | **1** | **1** | **0.99** | **1.05** | **1.03** |
| | | | | **median** | **32 (31)** | **1** | **0.98** | **1** | **0.99** | **1.02** | **1** |
| | | | | **range** | **21–45 (21–36)** | **0.84–1.09** | **0.82–1.13** | **0.79–1.12** | **0.87–1.21** | **0.81–1.2** | **0.61–1.64** |

**[1]injured/uninjured**
**[2]dominant side in bold**
**[3]days from injury to cast removal (days from pin fixation to cast removal)**
**[4]sustained right index finger fracture 3 weeks before follow-up examination**
**na = not available**

**Figure 24**

**The two patients (Table 15, Cases 12 and 23) with the most pronounced radiographic deformity in both treatment groups with 5° of apex volar angulation of the radius (AB – cast immobilization in bayonet position, CD – reduction and pin fixation). Both patients reported normal pain-free injured upper limb functions at the mid-term follow-up (3 and 4.4 years).**



## 5.4 TREATMENT QUALITY OF DMRFOP (I–III)

In the following (Table 16) I have compared by Institute of Medicine (IOM) values the advantages and disadvantages of DMRFOP treatment by casting and pin fixation. Propositions are based on the results of studies I-III and my own experience during this doctoral dissertation work.

**Table 16**

**Comparison of advantages (+) and disadvantages (-) of DMRFOP treatment methods.**

| IOM-value | Casting in overriding position | Reduction and pin fixation |
|---|---|---|
| **Safe** | +minimal risk for additional injury during treatment<br>-possibly a higher risk for the compartment syndrome and nerve-related symptoms | -anesthesia- and iatrogenic injury risks |
| **Timely** | +treatment can be given immediately in ED | -operation can be done within 1–7 days |
| **Effective** | -injured distal forearm can be thicker or slightly curved right after immobilization | +right after immobilization, distal forearm appears normally aligned |
| **Efficient** | +can be carried out without local or general anesthesia, opioids and scars<br>+is not a traumatic for the child<br>+does not require hospitalization<br>+is a much cheaper treatment method | +requires anesthesia-related procedures (cannulating) can be traumatic for the child<br>-require local- or general anesthesia, most often strong opioids<br>-sometimes requires open reduction and pin insertions points cause scars<br>-often requires hospitalization 1–2 days<br>-is more expensive |
| **Equitable** | | |
| **Patient (family) centered** | +patient and her guardian can be together throughout the treatment<br>+easier and less time consuming for the family | -stressful for the patient and guardian<br>-requires on average more visits to hospital and 1–2 days hospitalization |

# 6 DISCUSSION

The incidence and etiology of DMRFOP have not been published before Study I, although distal radius is cited as the most common fracture localization in children and adolescents (Landin 1983). We found a mean annual incidence of 1.42/10,000 with a large annual variation between 0.72 and 2.01/10,000). The exact location of DMRFOP has not been previously reported either. According to the results of Study I, nearly all (93%) DMRFOP occur within the Li-La box, and the most frequent direction of displacement is dorsal. In other words, as interpreted by Graham (2022), most DMRFOPs occur within 2 cm of the distal radial physis. DMRFOP located proximal to distal radius metaphysis according to the Li-La classification (7%) might be better defined as junctional or diaphyseal fractures when evaluated from the perspective of remodeling potential, particularly in older children.

DMRFOPs have been traditionally treated by closed reduction and cast immobilization (McLauchlan 2002, Zamzam 2005). Several authors have recommended pin fixation of DMRFOP, because of a high risk of loss of reduction in the cast without internal fixation (Miller 2005, Zamzam 2005, Schneider 2007). On the other hand, prepubertal children have a remarkable remodeling potential of malunited distal forearm fractures (Do 2003, Miller 2005). Plánka et al. (2006) and Crawford et al. (2012) were the first to report treatment of DMRFOPs by cast immobilization after correcting only the angulation but not the displacement and shortening of the fracture. However, because of the lack of RCTs, there is so far no consensus about the optimal treatment of DMRFOP in children and adolescents (Marson 2021).

We do not know how common it is to have a uniform intra-institutional treatment policy of DMRFOPs in different pediatric hospitals. Treatment methods of DMRFOP in our institution during Study I in 2016–19 were based on individual attending surgeons' preferences, rather than on homogenous treatment policy. DMRFOPs were treated with several different methods either in the ED or in the OR, immobilized in various types of splints and casts for a non-standardized time. There was no implemented pain medication protocol either.

Correction of fracture displacement and shortening failed in our hands in half of the children in the ED. Some surgeons accepted achieved overriding alignment in some children. On the other hand, some surgeons preferred to proceed with a re-manipulation of the fracture under anesthesia in the OR—probably because complete displacement at presentation and non-anatomic reduction have been reported to increase the risk for loss of alignment during casting (Proctor 1993, Haddad 1995, McLauchlan 2002, Zamzam 2004). Loss of reduction did not occur with our patients' fractures that had been anatomically reduced, supporting these earlier findings. Our findings suggest that it may be best not to attempt formal reduction at all in pre-pubertal children but rather cast their DMRFOPs in an overriding position in the ED. On the other hand, older children's and adolescents' DMRFOPs should be reduced and internally fixed in the OR.

Secondary interventions, such as re-manipulations or corrective surgery after malunion of DMRFOP, are not uncommon (Miller 2005, Crawford 2012, Marson 2021). In our institution, during the 4-year-long study period, 31% of all DMRFOP patients had a second- and 4% a third intervention. Three of these cases were caused by technically poorly executed internal fixation.

The results reported by Crawford et al. (2012) without formal reduction were inspirational, because they suggested that painful manipulations either under local or general anesthesia and surgery could be avoided in children under 11 years of age with DMRFOP (Lohmander 2021). In addition, this treatment method is cheaper and significantly easier for patients and their families. However, Crawford et al. (2012) based their conclusions on the radiological findings at 1 year from the fracture but failed to measure their patients' hand, wrist, and forearm function after treatment. Patients' or their guardians' subjective opinion of the treatment or its outcome was not registered either (Crawford et al. 2012). This study fills this important knowledge gap and supports the conclusions of Crawford et al. (2012).

The results of Studies I-III show that significant practice variations in the treatment of DMRFOP, especially in prepubertal children, still exist. Regardless of the treatment method, the mid-term results in our patient population were good or excellent. The vast majority of the patients' guardians were satisfied with the given treatment and the functional and cosmetic outcome of their child's injured forearm. The results after leaving the fracture in an overriding position, compared to the outcome after pin fixation in Study III, were similar. Our patients treated with pin fixation had fewer complications (17%) compared with earlier reports of up to 38% risk of adverse events (Stahl 2001, Miller BA 2005, Battle 2007, Marson 2021). Reduction and pin fixation does not seem to result in superior outcomes compared to casting in an overriding position in the ED based on observational data. However, to confirm these findings, we feel justified to implement a RCT (Study IV) to compare pin fixation to casting DMRFOP without formal reduction in the ED in patients under 11 years of age.

Subjective and objective outcome measures are difficult to obtain in children with fractures because there are no validated or widely used patient-reported outcome instruments for pediatric fracture patients (Marson 2020, Lohmander 2021). We decided therefore to choose forearm and wrist ROM, measured 6 months after the injury, as primary outcomes in the planned RCT. We do, however, realize that it is not easy to measure forearm and wrist motion reliably in children. This became apparent when conducting Study III: participants tended to position their upper limbs sub-optimally for photography without careful guidance, and it was difficult for young children to co-operate long enough to record forearm and wrist ROM from both the injured and uninjured side separately as planned. We thus decided to designate the ratio of forearm and wrist ROM of the injured/uninjured side as the primary outcomes for the planned RCT. Therefore, testing and documentation of participants' forearm ROM with photographs is an essential aspect of the reliability of the results of the RCT.

The definition of the non-inferiority-margin is essential in the interpretation of our RCT (Study IV) because it draws a line between acceptable and unacceptable results. We decided to use a 10% decrease in wrist and active forearm ROM compared to the healthy side as the non-inferiority margin. This is based on the findings of Nilsson and Obrant (1977), who reported that less than a 20° reduction of forearm rotation does not cause functional problems in children. Total forearm pro-supination is normally about 160°–170°, but it appears that children and adolescents need only 50° of both pronation and supination to accomplish activities of daily living (Valone 2020). The 10% difference between the injured and uninjured forearm ROM equals about 16°–17°, which means that our non-inferiority margin limit is smaller than what is important for children.

This thesis supports the concept that most DMRFOPs in children up to 10 years old can be treated without reduction and surgery with satisfactory outcomes. As it stands today, the treatment methods vary both within institutions and between different hospitals, reflecting the lack of convincing evidence to support one treatment over another. To address this, we have planned a RCT. This study has the potential to change clinical practice.

## 6.1 STRENGTHS AND LIMITATIONS OF THE STUDY

The strengths of the presented studies are:

1. We are confident that we have sorted out a population-based incidence of DMRFOP in the under-16 census population in Helsinki because private clinics around the catchment area do not have on-call anesthesia or pediatric orthopedic services and therefore refer children with displaced fractures to New Children's hospital.
2. The follow-up rate in Study I was high (89%). We therefore believe that our results showing generally good outcomes in DMRFOP regardless of the treatment method, if properly executed, are reliable.
3. We believe that the results of our survey (Study II) reflect the current preferred treatment of DMRFOP in patients under 10 years of age in Nordic countries and North America, because respondents were attendees of the annual European Pediatric Orthopedic Society's

meeting or surgeons in the most prominent Nordic or North American pediatric hospitals.

4. We could assess the outcome of 12/13 children whose DMRFOP were treated without reduction in a cast and compare it to the outcome of 12 age-matched children with similar DMRFOP treated with reduction. Study III is the first research ever to compare these two treatment methods to one another.
5. Outcomes in Studies I and III were not obviously superior in surgically treated children compared to children whose DMRFOP were cast in overriding position. We have thus designed a high-quality RCT (Study IV) to confirm the results of Studies I and III.

The limitations of these studies are:

1. There was no uniform treatment scheme for overriding distal radial fractures in our hospital, and the potential for selection, indication and even expertise bias exists in Study I.
2. It is impossible to assess how many of the secondary interventions in Study I were necessary, i.e., if they affected the functional outcomes, and the findings might be different in other hands.
3. The small number of participants in Study III caused imprecision in the estimates and makes the study sensitive to random error. Furthermore, the fixation was not performed in a uniform way in the pin-fixation group
4. Those 12 patients treated with reduction and pin fixation represent only 39% of all pin-fixed patients in our institution during the Study III period, and therefore the overall results of pin-fixed patients may not reflect the true outcomes.
5. Our method for measuring the wrist extension-flexion and pro-supination movement has not been validated (Study III).
6. The method for measuring wrist extension-flexion movement in Study IV is not yet validated.
7. At the time of RCT planning, there is no validated and widely used patient-reported outcome instrument for pediatric fracture patients (Study IV).

## 6.2 FUTURE ASPECTS

Patients' and guardians' subjective assessments of patients' pain during immobilization were not recorded in this study, and they have not been recorded in previous publications either. Secondly, there is little information regarding the return of forearm function after cast removal. We will address these questions in Study IV.

Our outcome measures, wrist extension-flexion measurement method, and QuickDASH will need to be validated before analyzing the results of Study IV.

We have evidence that traditional thinking (that DMRFOP also in prepubertal children should be reduced) is wrong, if casting DMRFOP in children under 11 years of age without reduction in overriding position yields non-inferior outcomes compared to reduction and pin fixation. In this case additional studies are necessary to further define the skeletal maturity stage of the patient when no reduction of DMRFOP is still a safe option.

On the other hand, if reduction and pin fixation of DMRFOP proves superior to casting in overriding position without formal reduction, traditional thinking should probably prevail, obviously depending on how superior surgery might prove to be. Risks and costs of anesthesia and internal fixation should then be weighed against the possibility of somewhat inferior functional outcome.

# 7 CONCLUSIONS

The population-based annual incidence of DMRFOP in children and adolescents under-16 census population in the city of Helsinki varied between 0.72 and 2.01/10,000/year during the study period 2014–19. Most (73%) DMRFOP occur in children under 11. Reduction of DMRFOP is difficult, especially in the ED, where it often fails. Local and general anesthesia, opioids, hospital admission and secondary interventions can be avoided in pre-pubertal children by casting DMRFOP in overriding position in the ED. Outcomes of non-operative and properly executed operative treatment appear to be generally good.

Based on the results of Study II, the most common current treatment method of DMRFOP in children under 10 in Nordic countries and North America is still reduction under general anesthesia and immobilization with an above-elbow cast. Percutaneous pin fixation is popular in Nordic countries. Only a few surgeons would treat DMRFOP without reduction with casts. There is no consensus about the type of cast, the length of immobilization, or the number of follow-up examinations. The publications of Plánka et al. (2006) and Crawford et al. (2012) have thus not led to a change in treatment praxis yet.

The results of Study III did not suggest superiority of reduction and pin fixation over cast immobilization in overriding position of closed DMRFOP in children under 10 years of age.

Based on the results of Studies I–III, a RCT comparing casting and pin-fixation treatment methods in patients under 11 years of age is justified. In the planned RCT (Study IV) we expect that primary outcomes in the casting group will be non-inferior to the surgery group at six months.

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The rest of acknowledgments I decided to write in Finnish, because it is the language of my feelings.

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Topi

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