Long-Term Follow-Up of Pediatric Forearm Fractures

Linde Musters

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Lange termijn resultaten van onderarmbreuken bij kinderen

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Thesis

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Promotor:	Prof. dr. D. Eygendaal
Other members:	Prof. dr. M. Verhofstad Prof. dr. S.M.A. Bierma-Zeinstra Prof. dr. J.N. Doornberg
Co-promotors:	Dr. J.W. Colaris Dr. M. Reijman

PROPOSITIONS/ STELLINGEN

1. Children with minimally displaced metaphyseal both-bone forearm fractures should be treated with a below-elbow cast (this thesis).
2. Forearm rotation impairment following a non-reduced diaphyseal fracture in both-bone forearm fractures will improve with time, regardless of the initial treatment (this thesis).
3. The cast for reduced stable diaphyseal both-bone forearm fractures should be switched to a below-elbow cast after three weeks (this thesis).
4. Current guidelines should be revised per the latest literature, which suggests a greater tolerance for increased angulation in most pediatric forearm fractures (this thesis).
5. Long-term functional impairment of forearm fractures can be predicted by complete initial displacement of the radius, refracture, diaphyseal location, and bicortical ulnar involvement (this thesis).
6. There should be a lower threshold for surgical fixation of both bone forearm fractures in obese children (Okoroafor et al).
7. Routine MRI for patients with a suspected scaphoid fracture leads to overdiagnosis (Bulstra et al).
8. Local blocks are just as effective as procedural anesthetics when performing a closed reduction of a pediatric forearm fracture in the emergency department (Sulton et al).
9. Marginal resection of high-grade chondrosarcomas is associated with more local recurrence but not with lesser overall survival (Chen et al).
10. Patients with a joint-specific pain scale pre-surgery of <3.5 for a total hip replacement and <6.5 for a total knee replacement do not benefit from an arthroplasty surgery (Langenberger et al).
11. Judge your success by what you had to give up in order to get it (Dalai Lama).

TABLE OF CONTENTS

Chapter 1

General introduction and goal of the thesis

GENERAL INTRODUCTION

Forearm fractures involving both bones constitute 40% of all pediatric fractures (1), with a higher incidence in boys. These fractures are located in the distal radial epiphysis in 14%, in the distal metaphysis in 65%, in the diaphysis in 20% and in the proximal metaphysis in one percent of the cases (2)(figure 1). Fracture patterns are a consequence of the force direction and magnitude applied to the bone. Pediatric bone has more elastic capacity than bones in adults, but when the bone is bent beyond its maximum elasticity by traumatic forces (150% of body weight), hundreds of micro-fractures appear, leading to irreparable damage and resulting in remaining bowing ('plastic deformity').
As more energy is applied, the bone will buckle on the compression side. Eventually, the bone gives way on the tension side, while the compression side continues to bend, resulting in the distinctive greenstick fracture. Finally, this will lead to a complete fracture on both sides (3) (figure 2).

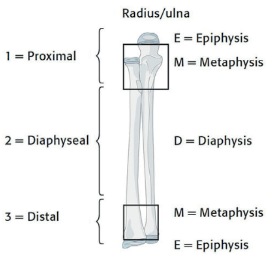

Figure 1. Anatomical nomenclature forearm. Copyright by AO Foundation, Switzerland. Source: AO Surgery Reference (https:// surgeryreference.aofoundation.org).

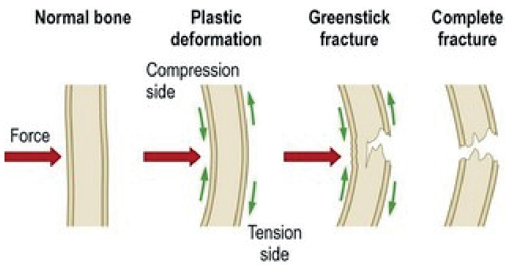

Figure 2. Increasing force leading to different type of pediatric fractures. Copyright by Musculoskeletal key (https://musculoskeletalkey.com/childrens-fractures).

Growth and remodeling distinguish pediatric from adult fractures and result in different decision-making when it comes to treatment (4).

The younger the child and the closer the fracture is to the physis, the greater the capacity for remodeling.
There are two mechanisms, based on two different laws in nature, that are responsible for the (correction by) growth in pediatric bone;

1. Wolff's law; the remodeling capacity of the periost. This takes mainly place at the diaphyseal level. Bone is being formed where biomechanically needed and resorbed where it is not needed. Forces responsible are compression on the concave side and pulling force on the convex side (5).

2. Hueter-Volkmann's law; the remodeling of the physis. This takes mainly place mainly at the epiphyseal level. Growth plates on both side of the fracture have a strong biological urge to supply growth correction. The growth plate wants to be perpendicular to the shaft. And the growth plate will supply whatever growth needed to achieve this (6).

Overall, pediatric fractures exhibit a very good remodeling capacity. This remodeling capacity at certain age is different in boys and girls, because their physis closure occurs at different ages; approximately 14.5 and 12.9 years, respectively (7).
Besides the potential of correction by growth in younger children, treatment of forearm fractures depends on various other aspects; including which injured bone (radius, ulna, or both), location (distal/proximal and epiphysis/metaphysis/diaphysis), type of fracture (bowing, buckle, greenstick, complete or with involvement of the physis), the amount of displacement (angulation, translation, rotation), the stability, and any associated dislocation (Galeazzi, Monteggia).
The most common treatment is immobilization in a cast. The options include a below-elbow cast (BEC), which extends from the hand to the elbow, or an above-elbow cast (AEC), reaching over the elbow until the armpit (Figure 3). The treatment dilemma arises from the fact that wearing a cast can cause discomfort, such as skin irritation in the elbow crease, itch around the edges of the cast, and a feeling of heaviness especially when the elbow is immobilized as well. One can imagine that this has a negative impact on the daily life of playing children.
In some specific cases an above-elbow cast might be indicated, as it controls both elbow and forearm range of motion by neutralizing muscles forces that originate above the elbow and is thought to reduce the risk of (secondary) fracture displacement (8)(9).

The current tendency is to immobilize as few joints as possible, to prevent unnecessary stiffness and optimize comfort (10). In most common pediatric fractures early conversion to below-elbow cast is favorable because it actually results in more comfort and even less secondary displacement in short-term follow-up (10–13).

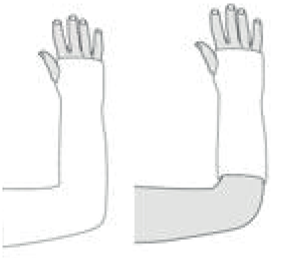

Figure 3. A. Above-elbow cast (AEC). B. Below-elbow cast (BEC). Copyright by AO Foundation, Switzerland. Source: AO Surgery Reference (https:// surgeryreference.aofoundation.org).

The types of fractures addressed in this thesis include distal radial physis fractures, buckle fractures, greenstick fractures, complete distal radius fractures, plastic deformation, complete metaphyseal both-bone fractures, complete diaphyseal both-bone fractures and radial neck fractures (figure 4). Galeazzi, Monteggia, radial head, and proximal fractures are omitted from this overview, as they are located around the elbow and with possible involvement of a dislocation mechanism which requires different treatment approaches.

Figure 4. Common types of pediatric forearm fractures. A. Radial physis fracture B. Buckle fracture. C. Greenstick fracture D. Complete distal radial fracture. E. Plastic deformation (Bowing). F. Complete metaphyseal both-bone fracture. G. Complete diaphyseal both bone fracture. H. Radial neck fracture.

Treatment

Distal metaphyseal fractures

These fractures include the distal one-third of the forearm. The most distal type is the distal

radial fracture with involvement of the distal physis. These fractures are classified using the Salter-Harris (SH) classification. SH fractures that present with (re)displacement older than 1 week should not be reduced to prevent physeal damage by remanipulation.
Minimally displaced metaphyseal fractures of one and/or two bones (greenstick, buckle, complete) without involvement of the physis are commonly treated with a below-elbow cast (13–18). Displaced fractures are often treated with a closed reduction and BEC or AEC. However, a systematic review by Sengab et al. showed that re-displacements can occur in up to 45.7% after closed reduction and cast, compared to only 3.8% in the group that underwent additional k-wire fixation (19) (figure 5a). If re-displacement is not treated promptly, this can result in a long-term malunion. Malunions angulated >16° can in their turn result in a clinically relevant limitation in forearm rotation in up to 60% of the children in short-term follow-up (18).

Diaphyseal fractures
These fractures involve the middle one-third of the forearm. Usually, un-displaced (or stable after reduction) diaphyseal forearm fractures of both bones are treated with an above-elbow cast (AEC) for 6 weeks, but recent literature suggests early conversion to a below-elbow cast (BEC)(10). In case of instability of one/both of the fractures after reduction, intramedullary nails are advocated to stabilize the fracture (20,21). Although there is an increasing tendency to treat diaphyseal forearm fractures with intramedullary nails (figure 5b), stable fractures after reduction can still be treated with cast (22). The disadvantage of treatment in a cast remains the risk of fracture re-displacement, which has been described in up to 7-39% (22–24). Re-displaced fractures, accepted as is and not treated with re-manipulation or surgical stabilization often result in malunion and impaired forearm rotation (11,25–30). The underlying mechanism of impaired forearm rotation seems to be minimal remodeling due to the far distance to the growth plates leading to persistent malunion, combined with contractures of the soft tissues like the interosseous membrane (31).
Bowing fractures, already discussed prior, need to be addressed in a different way, because of their reduced remodeling capacity. To reduce this type of fracture the same amount of force needs to be applied as it was bent with initially (32,33). It is crucial to recognize bowing fractures as they might result in cosmetic deformity, and painful impaired pro-supination (34,35). The consensus for treatment is closed reduction with short-term immobilization in a plaster when there is a pro-supination loss (33).

The final fracture to discuss is the radial neck fracture. When angulated <30 degrees these are treated conservatively with an above-elbow cast for 3 weeks. When angulated >30 degrees these need a closed or even open reduction with/without k-wire fixation or retrograde intramedullary fixation (36).

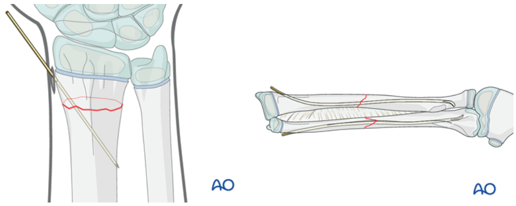

Figure 5. A. K-wire fixation . B. TENS nails fixation. Copyright by AO Foundation, Switzerland. Source: AO Surgery Reference (https://surgeryreference.aofoundation.org).

Early studies have highlighted a significant association between age and the ability to correct deformities. Children under the age of nine can achieve almost full correction of their malunion with remodeling capacity diminishing after the age of nine. Furthermore, older children with residual angulation have more limitations in pronation and supination (29,37).
Even if an angulation does not fully remodel, most children(>90%) with malunions have an excellent functional outcome with a discernible impact on daily life use (38,39).
The currently acceptable angulation differs per type and location of the fracture and the age of the patient. The latest overview in literature is by Ploegmakers et al 2006, therefore an up-to-date search of literature seems sensible, for insights have changed over the years (40).

This thesis presents a summary of long-term 7-year follow-up data on outcomes of treated forearm fractures in children, considering the effect of growth and remodeling. Seven-year follow-up studies in pediatric populations are scarce. The main reason is the loss to follow-up of patients. Young patients (and their parents) are not very motivated to return to the hospital for additional assessments, especially if they have no complaints. This can lead to potential effects of attrition, that need to be addressed in the analysis of data. Long-term follow-up is important in children, due to their high life expectancy; any improvement of function and quality of life should be weighted more heavily than in adults.

OUTCOMES

To determine the outcome of different treatment modalities the following outcomes are used: differences in forearm rotation compared to the contralateral uninjured arm, loss of flexion-extension of the elbow and wrist compared to the contralateral forearm, grip strength (using a JAMAR Dynamometer) displayed as a ratio of affected forearm/ contralateral side, the quick DASH, the ABILHAND-kids questionnaire, and radiological assessment of the angulation of radius and ulna (4,30,41–43).

AIMS AND OUTLINE OF THIS THESIS

This thesis will elaborate further on the relation between age and nature's ability to correct bony deformities and also on the functional outcome of malunited forearm fractures. Taking growth and remodeling into consideration, we try to elaborate on the acceptable age-related angulation for most common pediatric forearm fractures to treat the patients conservatively with a cast.
This subject will be outlined by answering the following two questions.
Does the long-term follow-up support early conversion from an above-elbow to a below-elbow cast for both-bone forearm fractures?
Which factors are important to take into consideration when treating forearm fractures, as they might influence the long-term outcomes?

The thesis aims to provide doctors with unique information on the behavior of the pediatric skeleton in response to fractures of the forearm. The aim is to inform doctors on when, how and how long to treat common pediatric forearm fractures and which factors to take into consideration when deciding on treatment.

We started with the long-term results of a multi-center RCT comparing an above-elbow cast with early conversion to a below-elbow cast for minimally displaced metaphyseal both bone forearm fractures **(Chapter 2)**, followed by the most optimal treatment for displaced metaphyseal forearm fractures **(Chapter 3)**. Then we continued with the other main group, the diaphyseal forearm fractures. This long-term follow-up RCT looks at early conversion to a below-elbow cast for non-reduced diaphyseal fractures, taking growth and remodeling capacity into account **(Chapter 4)**, followed by the long-term results of an RCT that discusses the treatment of reduced stable diaphyseal fractures **(Chapter 5). Chapter 6** discussed the outcome of a frequently missed type of pediatric fracture; the bowing or plastic deformity of the forearm. To address this, a systematic review of the literature was conducted to examine outcomes. **Chapter 7** presents a systematic review of the acceptable angulation of the most prevalent pediatric forearm fractures. Finally, **Chapter 8** elaborates on which factors affect the functional outcome in common pediatric forearm fractures. We conclude with **Chapter 9**, a scoping general discussion where the most important findings of the thesis are summarized as clinical implications and future perspectives are discussed.

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Part I

Long-term follow-up of distal metaphyseal forearm fractures

Chapter 2

Below-elbow cast sufficient for treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children: long-term results of a randomized controlled multicenter trial.

Linde Musters
Leon W Diederix
Kasper C Roth
Pim P Edomskis
Gerald A Kraan
Jan H Allema
Max Reijman
Joost W Colaris

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ABSTRACT

Background and purpose We have previously shown that children with minimally displaced metaphyseal both-bone forearm fractures, who were treated with a below-elbow cast (BEC) instead of an above-elbow cast (AEC), experienced more comfort, less interference in daily activities, and similar functional outcomes at 7 months' follow-up (FU). This study evaluates outcomes at 7 years' follow-up.

Patients and methods A secondary analysis was performed of the 7 years' follow-up data from our RCT. Primary outcome was loss of forearm rotation compared with the contralateral forearm. Secondary outcomes were patient-reported outcome measures (PROMs) consisting of the ABILHAND-kids and the DASH questionnaire, grip strength, radiological assessment, and cosmetic appearance.

Results The mean length of FU was 7.3 years (5.9–8.7). Of the initial 66 children who were included in the RCT, 51 children were evaluated at long-term FU. Loss of forearm rotation and secondary outcomes were similar in the 2 treatment groups.

Interpretation We suggest that children with minimally displaced metaphyseal both-bone forearm fractures should be treated with a below-elbow cast.

INTRODUCTION

Long-term follow-up of children with forearm fractures is scarce but essential, because the remodeling capacity by growth can behave as a friend or an enemy. Previous studies with short-term follow-up shown that metaphyseal both-bone fractures of the distal forearm could safely be treated with a below-elbow cast (BEC) (1–5)(6). Our previous randomized multicenter controlled trial compared BEC with above-elbow cast (AEC) for the treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children. This RCT concluded that children with minimally displaced metaphyseal both-bone fractures of the distal forearm should be treated with a below-elbow cast (7). We now report the long-term 7 year follow-up of these two treatment groups regarding loss of forearm rotation, patient reported outcomes measures (ABILHAND-kids questionnaire and DASH questionnaire (8–10) grip strength, radiological assessment and cosmetic appearance (1,3,7)(4,5).

PATIENTS AND METHODS

Trial design and participants

All patients who had been previously included between 2006 and 2010 in the RCT were invited to our outpatient clinic to determine long-term clinical outcomes with a minimum follow-up of 5 years (2). These patients had been children with a minimally displaced metaphyseal fracture of the radius and ulna, who had been randomized between treatment with AEC or BEC. An informed consent was again obtained from all the participants and from all the parents of children aged <12 years.

Outcomes measures

Our primary outcome measure was loss of forearm rotation in comparison to the contralateral side. Secondary outcome measures were patient-reported outcome measures (PROM's): using the Dutch version of the DASH and ABILHAND-kids questionnaire, wrist and elbow range of motion, grip strength (using a JAMAR Dynamometer), VAS scores regarding cosmetic appearance (scars and angulation of the forearm) and radiological assessment of malunion(9–11).

An orthopedic surgeon (LD) measured forearm rotation, flexion and extension of wrist and elbow using visual estimation and a goniometer with increments of 2 degrees. The follow up was organized in the patient's original hospital of inclusion. Both arms were examined to determine functional loss. Grip strength was measured using a JAMAR dynamometer, conducting one measurement comparing both arms. Patients were asked to fill in 2 PROM's, the DASH and the ABILHAND-kids questionnaire, and a VAS for cosmetic appearance. Cosmetic appearance was assessed by the patient, or by the parents in children <12 years, and by the investigator

(LD).
The radiological assessment consisted of a posteroanterior and lateral radiograph of the wrist. One of the authors (PE), measured the angulation of the radius and ulna (12,13).

Statistics
To evaluate whether the included patients in the current study are representative for the total initial study population of 66 patients, we compared the baseline characteristics, functional outcome and complications at short-term follow-up (7 months) between the included patients versus those lost to follow-up. Long-term results of primary and secondary outcome measures of the 2 treatment groups (AEC vs. BEC) were compared. Differences were analyzed using 1-way ANOVA to correct for multiple comparisons. Results are presented as mean SD or 95% confidence interval (CI). To assess the inter-rater reproducibility of radiographic assessment 2 authors (PE and LD) measured angulations of the radius and ulna of 25 cases (at cast removal and at final follow-up). Intra-class correlation coefficient was calculated. Statistical analyses were performed using IBM SPSS Statistics version 23.
Ethics, funding and potential conflict of interest
The original RCT was registered in ClinicalTrials.gov NCT 00397995. Ethics approval was obtained for this post-trial FU study with protocol number NL41839.098.12. This study complies with the CONSORT statement (14).
None of the authors or the authors' institutions has a financial or other relationship with other people or organizations that may influence this work.

RESULTS

Between 2006 and 2010 66 children were included in the RCT by Colaris et al. (2012) and 51 children participated in this current study. This long-term follow-up was performed in 26 out of 31 patients who were allocated to AEC, and 25 out of 35 patients who were allocated to BEC. The mean length of follow-up was 7.3 (5.9-8.7) years. Baseline characteristics of the groups and primary outcome, the loss of forearm rotation, showed no statistically significant differences between the two treatment groups (Table 1, 2) Analysis of secondary outcomes revealed no statistically significant differences between the 2 treatment groups (Table 3). No statistically significant differences were found in sagittal or coronal angulation of the radius and ulna in both groups (Table 4). The interrater reproducibility of the radiological assessment showed an intra-class correlation of 0.83 (CI 0.57 – 0.94).

DISCUSSION

We present the results of a multicenter randomized controlled study with a 7-year follow-up, concerning children with a minimally displaced metaphyseal both-bone fracture of the distal forearm who had been treated with either AEC or BEC. Short-term follow-up of these patients at 7 months showed no statistically significant differences, except more cast comfort and less interference with daily activities in the group treated with BEC. The 7-year follow-up revealed similar outcome between the 2 groups concerning loss of forearm rotation, patient-reported outcome measures (PROM's): DASH and ABILHAND-kids questionnaire, grip strength (using a JAMAR Dynamometer), VAS scores regarding cosmetic appearance (scars and angulation of the forearm) and radiological assessment of malunion.

Previous research with short-term follow-up

A meta-analysis by Hendrickx et al> included 3 RCTs comparing AEC to BEC for the treatment of both-bone distal forearm fractures in 219 children. Secondary fracture displacement was seen in 15% in the BEC group and in 28% in the AEC group. An update of this meta-analysis which included 2 more studies with 174 more children found no treatment preference anymore. Concerning the plaster-related complication rate, data was pooled and showed no difference between the 2 treatment strategies (4,5).

Previous research with long-term follow-up

Literature on long-term follow-up of non-operative treatment of forearm fractures in children is scarce. A retrospective study of Zimmerman et al. included 220 children with 232 distal forearm fractures between 1980-1992. The mean age of included children was 9 years (1-16) and the mean time of follow-up 10 years (5-16)(13). In 40 children both the radius and ulna were fractured. The purpose of this study was to investigate the frequency and extent of clinical and radiological late sequelae and identify predicting factors. The overall outcome was very good in 72%, and children < 10 years of age showed more favorable results, even with a malunion. Children >10 years of age with an angulatory deformity >20 degrees and/or more than 50% displacement at consolidation showed more pain and less function. Further factors having a negative influence on the outcome were repeated reduction and an additional fracture of the ulna.

We would like to address the ongoing debate about how much fracture angulation can be accepted at what age. The highest remodeling capacity is expected in young children with fractures close to the most active distal growth plate, and angulation in the sagittal plane. However, the literature on acceptable angulation in pediatric forearm fractures is scarce. Ploegmakers and Verheyen carried out a meta-analysis and together with the opinions of 18 international experts an effort was made to provide insight into the limits of acceptance of angular deformation in the non-operative treatment of pediatric forearm fractures(14). More specifically for metaphyseal both-bone fractures of the distal forearm, literature showed acceptable angulation of 11-18 degrees, compared to 6-24 degrees by the experts.

Our primary inclusion criteria (fracture angulation <15 degrees in children <10 years and <10 degrees in children >10 years) were in the range of these results. Our good clinical and radiological long-term follow-up results combined with previous literature (14,15) show that metaphyseal both-bone fractures of the distal forearm especially in children <12 years of age remodel satisfactorily (15).

Study limitations

Our main limitation is the long-term follow-up percentage of only 77%, but previous literature on acceptable loss to follow-up suggests that up to 40% loss to follow-up results in minimal attrition of the results(16,17). To address the potential effects of loss to follow-up we did a patient group analysis, which showed that the follow-up group was representative for the whole original study group.

Limitations of the original study still apply. The reduction criteria were only adjusted to 2 age groups without gender distinction, and the reduction criteria were used for both metaphyseal and diaphyseal forearm fractures. Therefore, the reduction criteria for metaphyseal fractures in the youngest children, especially boys, could have been probably too strict.

CONCLUSIONS

At long-term follow-up we found similar loss of forearm rotation after treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children treated with AEC or BEC. Furthermore patient-reported outcome measures and radiological assessment were similar. Based on short- and long-term results, we suggest that children with minimally displaced metaphyseal both-bone forearm fractures should be treated with a below-elbow cast.

AUTHOR CONTRIBUTIONS

LM writing, data analysis, submitting; LD writing, data analysis; KR data analysis; GR reviewer, writing; JA reviewer, writing; JC reviewer, writing

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Table 1. Baseline characteristics of the population. Values are numbers unless otherwise specified.

Baseline	Below elbow cast	Above elbow cast
Number of children	25	26
Age at trauma (SD)	7.5 (1.4)	6.2 (1.4)
Male sex	12	10
Dominant arm	5	10
Type fracture, radius		
Buckle	0	0
Greenstick	16	17
Complete fracture	9	7
Type fracture, ulna		
Buckle	2	4
Greenstick	19	19
Complete fracture	4	3

n= number of patients, AEC= Above Elbow Cast, BEC= Below Elbow Cast, SD=Standard Deviation

Table 2. Rpresentation of follow-up population

Outcome at 7 months follow-up	Lost to FU (95% CI) n=15		Included (95% CI) n=51	Total (95% CI) n=66
Age at trauma, years	7.9 (6.1 – 9.8)	6.8 (5.8 – 7.8)		7.1 (6.2 – 7.9)
Male sex, n	8	29		37
Forearm rotation 7 months, (°)	148 (144 - 153)	139 (131 - 148)		146 (142 - 150)
Loss rotation, (°)	4.9 (2.9 – 6.9)	4.3 (0.6 – 8.1)		4.8 (3.1 – 6.5)
ABILHAND-kids questionnaire (points)	41,4	41,7		41,6
Complications (%)	13	16		15
VAScosmetics parents/child (0-10)	9,6	9,4		9,4
VAS-cosmetics surgeon (0-10)	9,8	9,7		9,7

Table 3 Data (95% confidence interval) on primary and secondary outcomes at long-term follow-up

	Below elbow cast n = 25	Above elbow cast n = 26
Age at follow-up, years	14.9 (13.3 - 16.5)	13.2 (11.8 - 14.7)
Follow-up length, years	7.5 (6.9 - 8.0)	7.1 (6.5 - 7.7)
Loss of forearm rotation	-0.72 (-4.5 - 3.1)	0.58 (-5.1 - 6.2)
Loss of wrist flexion-extension	0.80 (-3.2 - 4.8)	0.58 (-2.4 - 3.5)
ABILHAND-kids questionnaire (points)	41.4 (40.1 - 42.7)	41.9 (41.5 - 42.3)
DASH score (points)	4.4 (0 - 13)	2.1 (0 - 6.9)
JAMAR score	31 (17 - 45)	28 (134 - 42)
VAS cosmetics parents (0-10)	9.4 (9.0 - 9.8)	9.3 (8.9 – 9.7)
VAS cosmetics surgeon (0-10)	9.7 (9.5 - 9.9)	9.6 (9.4 - 9.9)

Table 4. Radiological angulation (°) (95% confidence intervals)

	Below elbow cast		Above elbow cast	
	Cast removal	Final	Cast removal	Final
Anteroposterior				
Ulna	7 (2-12)	5 (2-8)	6 (2-10)	5 (2-8)
Radius	4 (0-8)	6 (3-9)	4 (0-8)	5 (1-9)
Lateral				
Ulna	6 (2-10)	4 (1-7)	6 (3-9)	4 (2-6)
Radius	10 (5-15)	5 (2-8)	10 (5-15)	4 (1-7)

Cast removal at 6 weeks after casting

Chapter 3

Do we need to stabilize all reduced metaphyseal both-bone forearm fractures in children with K-wires?

Leon W. Diederix
Kasper C. Roth
Pim P. Edomskis
Linde Musters
Jan Hein Allema
Gerald A. Kraan
Max Reijman
Joost W. Colaris

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ABSTRACT

Background Short-term follow-up studies have shown that reduced metaphyseal both-bone forearm fractures in children should be treated with K-wires to prevent re-displacement and inferior functional results. Minimum 5-year follow-up studies are limited. Range of motion, patient-reported outcome measures, and radiographic parameters at minimum 5-year follow-up should be evaluated because they could change insights into how to treat pediatric metaphyseal forearm fractures.

Questions/purposes (1) Does K-wire stabilization of reduced metaphyseal both-bone forearm fractures in children provide better forearm rotation at a minimum 5-year follow-up? (2) Do malunions (untreated re-displaced fractures) of reduced metaphyseal both-bone forearm fractures in children induce worse functional results? (3) Which factors lead to limited forearm rotation at a minimum 5-year follow-up?

Methods We analyzed the extended minimum 5-year follow-up of a randomized controlled trial in which children with a reduced metaphyseal both-bone forearm fracture were randomized to either an above-elbow cast (casting group) or fixation with K-wires and an above-elbow cast (K-wire group). Between January 2006 and December 2010, 128 patients were included in the original randomized controlled trial: 67 in the casting group and 61 in the K-wire group. For the current study, based on an a priori calculation, it was determined that with an anticipated mean limitation in pro-supination (forearm rotation) of 7° 6 7° in the casting group and 3° 6 5° in the K-wire group, a power of 80% and a significance of 0.05, the two groups should consist of 50 patients each. Between January 2014 and May 2016, 82% (105 of 128) of patients were included, with a mean follow-up of 6.8 6 1.4 years: 54 in the casting group and 51 in the K-wire group. At trauma, patients had a mean age of 9 6 3 years and had mean angulations of the radius and ulna of 25° 6 14° and 23° 6 18°, respectively. The primary result was a limitation in forearm rotation. Secondary outcome measures were radiologic assessment, patient-reported outcome measures (Quick DASH and ABILHAND-kids), handgrip strength, and VAS score for cosmetic appearance. Assessments were performed by the first author (unblinded). Multivariable logistic regression analysis was performed to analyze which factors led to a clinically relevant limitation in forearm rotation.

Results There was a mean limitation in forearm rotation of 5° ± 11° in the casting group and 5° ± 8° in the K-wire group, with a mean difference of 0.3° (95% CI -3° to 4°; p =0.86). Malunions occurred more often in the casting group than in the K-wire group: 19% (13 of 67) versus 7% (4 of 61) with an odds ratio of 0.22 for K-wiring (95% CI 0.06 to 0.80; p = 0.02). In patients in whom a malunion occurred (malunion group), there was a mean limitation in forearm rotation of 6° ± 16° versus 5° ± 9° in patients who did not have a malunion (acceptable alignment group), with a mean difference 0.8° (95% CI -5° to 7°; p = 0.87). Factors associated with a limited forearm rotation $ 20° were a malunion after above-elbow casting (OR 5.2 [95% CI 1.0 to 27]; p = 0.045) and a refracture (OR 7.1 [95% CI 1.4 to 37]; p = 0.02).

Conclusion At a minimum of 5 years after injury, in children with a reduced metaphyseal both-bone forearm fracture, there were no differences in forearm rotation, patient-reported outcome measures, or radiographic parameters between patients treated with only an above-elbow cast compared with those treated with additional K-wire fixation. Re-displacements occurred more often if treated by an above elbow cast alone. If fracture re-displacement is not treated promptly, this leads to a malunion, which is a risk factor for a clinically relevant (≥20°) limitation in forearm rotation at minimum 5-year follow-up. Children with metaphyseal both bone forearm fractures can be treated with closed reduction and casting without additional K-wire fixation. Nevertheless, a clinician should inform parents and patient about the high risk of fracture re-displacement (and therefore malunion), with risk for limited forearm rotation if left untreated. Weekly radiographic monitoring is essential. If re-displacement occurs, re-manipulation and fixation with K-wires should be considered based on gender, age, and direction of angulation. Future research is required to establish the influence of (skeletal) age, gender, and the direction of malunion angulation on clinical outcome.

Level of Evidence Level I, therapeutic study

3

BACKGROUND

Reduced metaphyseal both-bone forearm fractures have been shown to re-displace in a cast in up to 46% [9, 26] and have a 3.6 to 23 times higher risk for re-displacement than isolated distal radius fractures [16, 31]. In 2013, we published [9] a randomized controlled trial (RCT) that included 128 children with a reduced stable metaphyseal both-bone forearm fracture who were randomized to an above-elbow cast (AEC) with or without percutaneous K-wire fixation. Children treated with an AEC alone had a higher risk of re-displacement and a high risk of limiting pro-supination (forearm rotation) than children with additional K-wire fixation, after a mean follow-up of 7 months. Thus, pinning of apparently stable both-bone distal forearm fractures in children was recommended to prevent re-displacement [9].

RATIONALE

There has been a recent increase in operative management to treat fractures in children, even though there have been no long-term outcome studies showing superior results following operative treatment [12, 14]. As mentioned, the goal of operative treatment is to prevent re-displacement. If re-displacement of a metaphyseal forearm fracture occurs after conservative treatment, a clinician has two options: to reduce the fracture again (with or without K-wire fixation) or to accept malunion and hope that the remodeling that occurs during growth will result in acceptable cosmetics and function (Fig. 1) [25]. Tremendous remodeling is especially apparent in young children (younger than 10 years) with a distal fracture near the most active growth plate [19, 27, 30]. Treatment discussion is ongoing about what degree of malunion results in an acceptable long-term clinical result [23, 32, 33]. A minimum 5-year follow-up should be evaluated because it could change insights into the treatment of pediatric metaphyseal forearm fractures.
Therefore, we asked: (1) Does K-wire stabilization of reduced metaphyseal both-bone forearm fractures in children provide better forearm rotation at a minimum 5-year follow-up?
(2) Do malunions (untreated re-displaced fractures) of reduced metaphyseal both-bone forearm fractures in children induce worse functional results? (3) Which factors lead to limited forearm rotation at a minimum 5-year follow-up?

PATIENTS AND METHODS

Study Design and Setting
We report the extended follow-up of a published RCT with a minimum follow-up of 5 years. Children with a displaced metaphyseal both-bone forearm fracture were included in one

of four participating Dutch hospitals: Erasmus Medical Center (Rotterdam), Haga Hospital (The Hague), Reinier de Graaf Hospital (Delft) and Franciscus Hospital (Rotterdam). Our initial institutional review board protocol did not specify another follow-up moment 5 years later. However, after finishing data collection of the original RCT, we thought this would be informative and initiated the current extended follow-up study. In the published RCT, between January 2006 and December 2010, 128 patients were included (67 in the AEC group and 61 patients in the K-wire group). For the current study, we invited all 128 patients to revisit the outpatient department. Between January 2014 and May 2016, 82% (105 of 128) patients were included: 54 of the AEC group and 51 of the K-wire group. A CONSORT flow diagram is supplied in Fig. 2.

Participants

In the original RCT, we included children younger than 16 years who had a displaced metaphyseal fracture of the distal radius and ulna. We included only children with displaced

forearm fracture that was stable after closed reduction in the operating room. The criteria for fracture reduction were defined a priori: a fracture was reduced if the radius and/or ulna showed displacement on a posteroanterior and/or lateral radiograph. Fracture displacement was based on angulation (< 15° for children aged younger than 10 years and < 10° for children between 10 to 16 years) and/or translation (more than half bone diameter) and/or any rotation. Fracture re-displacement was defined by the loss of reduction (angulation and/or translation) according to these primary reduction criteria [9]. Based on the occurrence of re-displacement, we divided all included patients into two additional groups (malunion and non-malunion group). Malunion was defined as the occurrence of fracture re-displacement, meeting the above-mentioned criteria for reduction, but was left untreated (contrary to RCT protocol) and thus consolidated in a malunited position.

Description of Treatment

All included patients underwent closed reduction. Thereafter, the fracture was tested for stability. The fracture was defined as unstable if full pronation and supination of the forearm caused re-displacement [9]. Unstable fractures were excluded and were treated with K-wire fixation. The remaining fractures were defined as stable and were randomized between AEC alone (AEC group) or K-wire pinning with AEC (K-wire group), both for 4 weeks.

Randomization

In the published RCT, participants were randomly assigned and treated in the AEC or K-wire group. An independent clinician randomized the children by sealed envelopes with varied block sizes. The children, parents and clinicians were not blinded for randomization. For the current RCT, we obtained informed consent from all parents and all children aged at least 12 years. Patients unable to attend were, if possible, interviewed via telephone to complete patient-reported outcome measure questionnaires.

Variables, Outcome Measures, Data Sources, and Bias

Our primary outcome measure was limitation in pro-supination (forearm rotation) compared with the contralateral side. Secondary outcome measures were radiologic assessment; patient-reported outcome measures, including the Dutch version of the QuickDASH questionnaire and ABILHAND-kids questionnaire [2, 3, 6]; handgrip strength percentage of the contralateral side; and the VAS score for cosmetic appearance. One unblinded orthopaedic surgeon (JC) examined all patients during short-term follow-up (mean of 7.1 months) after the initial trauma for the original RCT [9]. A second independent orthopaedic surgeon (LD) examined all patients at minimum 5-year follow-up (unblinded). Forearm rotation was evaluated using a standardized procedure: visual estimation and a two-increment goniometer [8]. Handgrip strength was measured using a JAMAR dynamometer. Cosmetic appearance (forearm morphology and possible scars) was assessed by the first author (LD) and either by the patient or by the parent, if the patient was younger than 17 years. This VAS was scored in the traditional way on a 10-cm line [13]. A score of 10 was defined as cosmetically best. Radiographic examination was performed. One of the authors (PE) measured the radiologic intramedullary angulation of the radius and ulna on posteroanterior and lateral radiographs taken at the time of cast removal (consolidation) and at the final follow-up [17]. Radiographic angulation was remeasured in 25 patients by the primary author (LD) to assess reproducibility.

Ethical Approval

Our institutional review board approved this post-trial follow-up study, which was registered under protocol number NL41839.098.12. The original RCT [9] was registered in ClinicalTrials.gov with registry identifier NCT 00397852.

Statistical Analysis, Study Size

In the previous RCT, after a mean follow-up of 7 months, a limitation of forearm rotation of 14° ± 14° was seen in the AEC group and 7° ± 9° in the K-wire group [9]. We expected that over time, the limitation of pro-supination would decrease by approximately 50% at a minimum 5-

year follow-up. With an a priori calculation, we determined that with an anticipated mean limitation in pro-supination of 7° ± 7° in the AEC group and an anticipated mean limitation in pro-supination of 3° ± 5° in the K-wire group, a power of 80% and a significance of 0.05, the two groups should consist of 50 patients each. It was established whether the variables had a normal distribution using the normality Shapiro–Wilk test. Based on these analyses, the results are presented as means ± SD, mean difference (95% confidence interval and p values. Patient demographics included for minimum 5-year follow-up were compared between the study groups (AEC group versus K- wire group) using the independent samples t-test (Table

1). Radiographic and functional results were analyzed using independent samples t-test for study groups (AEC group versus K-wire group) in Table 2 and for subgroups (malunion versus non malunion group) in Table 3. To assess the interrater reproducibility of the radiographic assessment, we calculated the intraclass correlation coefficient (Type C).

Multivariate logistic regression analysis was performed to analyze which factors led to a clinically relevant limitation in forearm rotation at minimum 5-year follow-up, defined as a limitation of forearm rotation ≥ 20° (as dependent variable), a cutoff point which has been used previously [10]. The following factors were included in our exploratory analysis (univariate logistic regression): intervention (AEC group versus K-wire group); occurrence of a malunion (malunion versus non-malunion group) and occurrence of a refracture (group versus non-refracture group), age at trauma (age younger than 10 years versus age 10 years or older) and sex (male versus female). A p-value < 0.05 during univariate logistic regression was used as a threshold to determine which factors progressed to the more definitive multivariate logistic regression analysis. Statistical analyses were performed using IBM SPSS Statistics, version 23.

Patient Demographics

Of the patients who were included in the original RCT [9], 82% (105 of 128) participated in the current study. Fifty-four of the original 67 participants who were allocated to the AEC group and 51 of the original 61 participants who were allocated to K-wire fixation and AEC participated. Eighteen percent (23 of 128) of patients were lost to follow-up. The mean length of follow-up was 6.8 ± 1.4 years. Baseline characteristics were similar between the groups (Table 1). At trauma, patients had mean angulations of the radius and ulna of 25° ± 14° and 23° ± 18°, respectively. The interrater reliability of the radiologic measurement had an intraclass correlation of 0.83 (95% CI 0.57 to 0.94). In the original RCT, in the AEC group, re-displacement occurred in 30 patients in the first weeks after trauma, 17 of whom underwent re-manipulation (six received additional K-wire fixation) and 13 of whom accepted re-displacement (the malunion group). Eighty-three percent (25 of 30) of patients with re-displacements were available for minimum 5-year follow-up. In this group of 25 patients, 14 patients underwent re-manipulation, and 11 patients accepted the re-displacement (the malunion group). Refractures occurred in 11 of 128 patients, nine of whom were reevaluated at final follow-up.

RESULTS

Does K-wire Stabilization of Reduced Metaphyseal Both-bone Forearm Fractures in Children Provide Better Forearm Rotation at Minimum 5-year Follow-up?

K-wire stabilization of reduced metaphyseal both-bone forearm fractures in children did not provide better forearm rotation at a minimum 5-year follow-up. There was a mean limitation in pro-supination in the K-wire group of 5° ± 8° and a mean limitation of 5° ± 11° in the AEC group with a mean difference of 0.3 (95% CI -3.3 to 4.0; p = 0.86) (Table 2). Radiographic results were similar. There was less residual angulation of the radius in the coronal plane in the AEC group (4° [95% CI 2.9° to 5.0°) than in the K-wire group (5° [95% CI 4.4° to 6.3°], mean difference -1.4 (95% CI -2.8 to 0.4; p = 0.04). We found no differences in patient-reported outcome measures (Quick DASH and ABILHAND-kids), VAS score for cosmetics and handgrip strength (Table 2).

Do Malunions of Reduced Metaphyseal Both-Bone Forearm Fractures in Children Induce Worse Functional Results?

Malunions of reduced metaphyseal both-bone forearm fracture in children occurred more often in the AEC group than the K-wire group at short-term follow-up: 19% (13 of 67) versus 7% (4 of 61) with an odds ratio of 0.22 for K-wires (95% CI 0.06 to 0.80; p = 0.02). At a minimum 5-year follow-up, there was a mean limitation of forearm rotation of 6° ± 16 in the malunion group versus 5° ± 9° in the non-malunion group, with a mean difference of 0.8 (95% CI -5.2° to 6.9°; p = 0.87). Angulation of the ulna in the sagittal plane was less in the malunion group (1° [95% CI -0.8° to 2.8°]) than in the non-malunion group (4° [95% CI 3.0° to 4.6°]), with a mean difference of -2.8° (95% CI 5.2 to -0.4°; p = 0.02). Patient-reported outcomes (Quick DASH and ABILHAND-kids), cosmetic appearances scores, and grip strength were not different (Table 3).

Which Factors Lead to Limited Forearm Rotation of More than 20°?

At minimum 5-year follow-up, two factors were associated with a clinically relevant limitation in forearm rotation of ≥ 20°: occurrence of a malunion after AEC (OR 5.2 [95% CI 1.0 to 27]; p = 0.045) and a refracture (OR 7.1 [95% CI 1.4 to 37]; p = 0.02). Limitation in forearm rotation ≥ 20° was seen in the malunion group in 27% (3 of 11) versus 7% (7 of 94) in the non-malunion group. Also, this limitation was seen in 33% (3 of 9) of patients in whom a refracture occurred versus in 7% (7 of 96) of patients without a refracture (Table 4). Sex and age at trauma older than 10 years were not associated with a limitation in forearm rotation ≥ 20° at minimum 5-year follow-up during exploratory univariate logistic regression analysis (p-values of 0.11 and 0.49, respectively).

DISCUSSION

Background and Rationale

Displaced metaphyseal both-bone forearm fractures in children, which are stable after closed reduction show high incidence of re-displacement in a cast, which can cause malunion and limitation in forearm rotation [9, 26]. Re-displacement can be prevented by K-wire stabilization.

To determine if K-wire stabilization is essential for all reduced metaphyseal both-bone forearm fractures in children or that such malunions will correct by growth, we reassessed ROM, patient-reported outcome measures, and radiographic parameters of patients included in our previous RCT after a minimum of 5-year follow-up.

Limitations

A key limitation is that we could not include enough patients to perform a powerful multivariable analysis including more potentially relevant factors, such as the direction of malunion angulation and degree of initial displacement, but also, we could not adequately control for patient's age and sex. Concerning direction of malunion angulation, Roberts et al. demonstrated that radial deviation is more closely related to loss of forearm rotation than dorsal angulation [24]. Zimmerman et al. compared palmar versus dorsal displaced pediatric metaphyseal radius fractures and found no differences in remodeling capacity, but they did find a higher restriction of supination in palmar displaced malunions [30]. Furthermore, the degree of initial angulation at trauma may be predictive for re-displacement risk after 1 or 2 weeks. Initial angulation may predict the degree of fracture stability. Although in our study female sex and being older than 10 years at trauma were not associated with a clinically relevant limitation in forearm rotation (≥ 20°), we still cannot assume the findings will apply equally to both sexes at any age. Girls can be more skeletally advanced than boys with the same age, as the mean age for ossification of the physis differs between boys and girls (14.5 and 12.9 years, respectively), which results in less remodeling potential [25]. Greater remodeling potential is generally found in patients with more residual growth, a smaller distance to the most active growth plate, and fracture angulation in the sagittal plane [16]. Therefore, in clinical practice, one should be cautious to apply our results especially to nearly skeletally mature girls with severe (radial or volar) re-displacement. A second limitation is that although the RCT protocol stated to perform re-manipulation in case of a re-displacement, 13 of 30 re-displacements were left untreated. This introduced a treatment bias because there may have been factors influencing a surgeon to accept the re-displacement (for instance younger age), which could skew the impact of that redisplacement on the ultimate clinical result. This indicates that the criteria for reduction possibly were too stringent. Furthermore, functional and radiologic assessments were not blinded and were performed by only one investigator. Blinded assessment was not possible because of the assessment of cosmetic appearance (including scars). The measurements of forearm rotation could also have inter- and intra-observer variations, thus our conclusions based on these measurements would be stronger if repeated measurements had been performed. Finally, below-elbow cast (compared with AEC) has been shown to be sufficient in treatment of distal forearm fractures in children, but this became apparent after initiation of our original RCT [4, 11, 29].

Does K-wire Stabilization of Reduced Metaphyseal Both-bone Forearm Fractures in Children

Provide Better Forearm Rotation at Minimum 5-year Follow-up?
Although this RCT showed superior results of stabilization with K-wires in addition to an AEC after 7 months of follow-up [9], a minimum 5-year follow-up stabilization with K-wires did not provide better forearm rotation, radiographic parameters, or patient-reported results. Therefore, children with a displaced metaphyseal both-bone forearm fractures can be treated with closed reduction and an AEC without K-wire fixation. Previously, one meta-analysis compared results of displaced distal radius fractures between children treated with an AEC versus K-wire fixation [26]. This meta-analysis included three RCTs [9, 20, 21], one prospective cohort study [15], and two retrospective cohort studies [22, 28]. In this meta- analysis, 76% (292 of 382) of included children had a both-bone forearm fracture. In the AEC group, the redisplacement proportion was 46% (90 of 197) patients versus 4% (7 of 185) in the K-wire group (OR 0.07 [95% CI 0.03 to 0.15]). Complications other than redisplacement occurred more often in the K-wire group than in the AEC group (15.7% versus 3.6%). In contrast to the study by Colaris et al. [9], the studies by McLauchlan et al. [20] and Ozcan et al. [22] found no differences in functional results between the two treatment groups at 3 and 20 months of follow-up, respectively. Based on the combined results of these three studies, Sengab et al. [26] concluded that K-wire fixation does not result in better ROM but leads to a lower redisplacement proportion and fewer reinterventions. This is consistent with our findings. Future research, such as a meta-analysis or a large prospective observational study, is required to establish the influence of (skeletal) age, gender, and the severity and direction of malunion angulation of both the radius and ulna on clinical result. Currently, we await the results of the AFIC RCT by Adrian et al., in which children (younger than 11 years of age) with displaced distal forearm fractures with up to 30° angulation are randomized between: cast immobilization versus closed reduction with or without additional K-wire fixation [1].

Do Malunions of Reduced Metaphyseal Both-bone Forearm Fractures in Children Induce Worse Functional Results?
Malunions lead to a higher incidence (27% versus 7%) of a clinically relevant limitation in forearm rotation (≥ 20°) at minimum 5-year follow-up. Our results, however, show no differences in mean limitations between the two groups (malunion versus non-malunion). This may seem contradictory, but it can be explained by the fact that most patients with a malunion (73%) still showed good forearm rotation at minimum 5-year follow-up, leading to a low mean limitation in forearm rotation of the whole malunion group. In clinical practice if fracture redisplacement occurs 1 or 2 weeks after the initial trauma, we advise to (based on sex, age and direction of angulation) consider remanipulation and K-wire fixation promptly to decrease the risk of developing a persistent limitation in forearm rotation. Earlier, Colaris et al. showed that pediatric metaphyseal both-bone forearm malunions angulated ≥ 16° developed a clinically

relevant limitation in forearm rotation in 60% after a mean follow-up of 7 months [7].

Which Factors Lead to Limited Forearm Rotation?
At minimum 5-year follow-up, factors associated with a clinically relevant limitation in forearm rotation were malunion after AEC and a refracture. A study performed by Zimmerman et al. revealed that children older than 10 years whose fractures healed with an angular deformity of more than 20° had the poorest long-term results, while in children younger than 10 years of age, angular deformity did not influence long-term results [32]. The occurrence of a refracture was also associated with limited forearm rotation of ≥ 20°, possibly explained by repeated immobilization in a cast leading to soft tissue contractures [10]. Refractures are eight times more likely to reoccur in diaphyseal fractures as in distal forearm fractures [5]. Diaphyseal fractures behave vastly different to metaphyseal forearm fractures. In 1962, Hughston claimed that in diaphyseal fractures “growth will not correct angulation deformity as it does in metaphyseal fractures” [18]. Because of the relatively long distance between a diaphyseal fracture and the growth plates, only minimal correction of malalignment by growth can be expected.

3

CONCLUSIONS

At minimum 5-year follow-up in children with metaphyseal both-bone forearm fractures that were stable after closed reduction, we found no differences in forearm rotation between treatment with only an AEC and treatment with additional K-wire fixation. Redisplacement occurs more often if treated by an AEC alone. If fracture redisplacement is not treated promptly, a malunion may occur which is a risk factor for a clinically relevant limitation in forearm rotation at minimum 5-year follow-up. Children with a displaced metaphyseal both- bone forearm fracture can be treated with closed reduction and an AEC without additional K- wire fixation. The clinician should inform parents and patient about the high risk of fracture redisplacement, which, if left untreated, results in malunion with risk for forearm rotation limitations. Weekly radiographic monitoring is essential. If redisplacement occurs, remanipulation and K-wire fixation should be considered based on sex, age and direction of angulation. Future research is needed to establish the influence of (skeletal) age, sex, severity of initial displacement and the direction of malunion angulation on clinical result.

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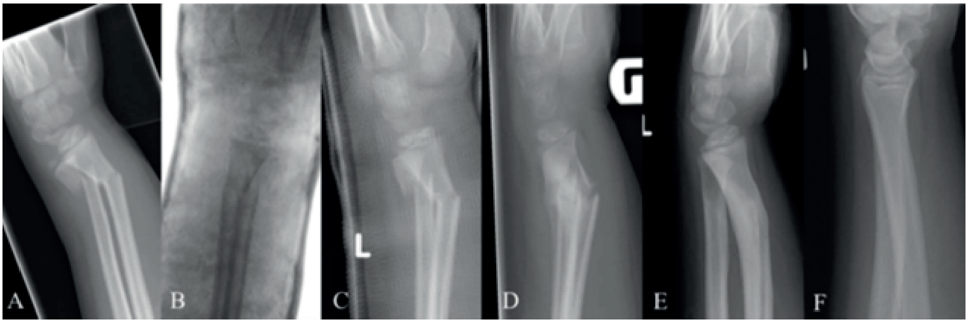

Fig. 1A-F These sagittal radiographs are from a patient with a displaced metaphyseal both-bone forearm fracture, including (A) an initial radiograph of the fracture, (B) after reduction,(C) redisplacement after 10 days, (D) 25 days after trauma, (E) 5 months after trauma, and (F)7.5 years after trauma.

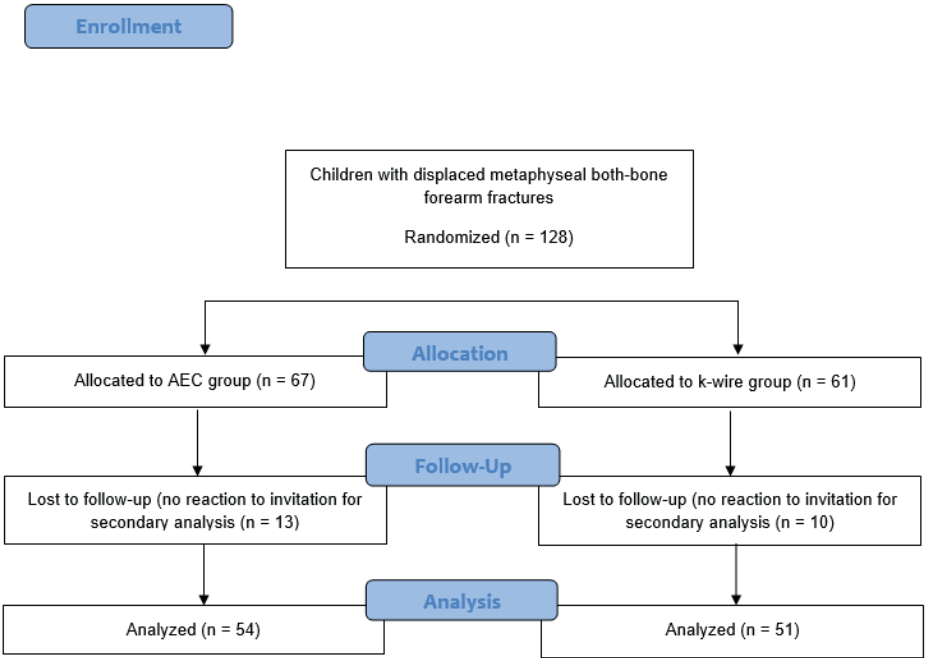

Fig. 2 This CONSORT study flow diagram demonstrates the selection and flow of patients.

Table 1. Patient demographics

Characteristic	Casting group (n = 54)	K-wire group (n = 51)	Mean difference (95% CI)	p value
Age at trauma, years	9 ± 3	9 ± 3	-0.4 (-1.6 to 0.8)	0.49
Sex (% male)	61 (33)	69 (35)	7.5% (-11 to 26)	0.43
Dominant arm	52 (28)	45 (23)	6.8% (-13 to 26)	0.49
Fracture type, radius				
Complete	76 (41)	84 (43)	19.1% (1 to 37)	0.04
Greenstick	24 (13)	16 (8)	-19.1% (-37 to -1)	0.04
Fracture type, ulna				
Complete	44 (24)	47 (24)	1.3 (-1.8 to 2.1)	0.89
Greenstick	50 (27)	45 (23)	-4.9 (-24 to 15)	0.62
Torus	6 (3)	8 (4)	3.6 (-3.9 to 11)	0.34
Angulation radius, °	27 ± 16	23 ± 15	4.6 (-0.9 to 10)	0.10
Angulation ulna, °	25 ± 21	20 ± 13	5.0 (-1.7 to 12)	0.15

Data presented as % (n) or mean ± unless noted otherwise

Table 2. Radiographic and functional results (casting vs K-wire group)

		Casting group (n=67)	K-wire group (n=61)	Mean difference (95% CI)	p value
Radiographic outcomes					
Consolidation[a]	Radius – PA	8° ± 7°	6° ± 4°	1.9° (-0.6° to 4°)	0.12
	Radius - lateral	13° ± 10	8° ± 4	5.0° (1.6 to 9)	0.01
	Ulna - PA	7° ± 4	6° ± 4	1.0° (-0.7 to 3)	0.25
	Ulna - lateral	7° ± 5	7° ± 5	0.5° (-2 to 3)	0.67
		(n = 54)	(n = 51)		
7-year follow-up	Radius – PA	4° ± 3	5° ± 3	-1° (-3 to 0.4)	0.04
	Radius - lateral	4° ± 3	4° ± 3	-0.4° (-2 to 0.9)	0.52
	Ulna - PA	5° ± 3	5° ± 3	-0.3° (-2 to 1)	0.68
	Ulna - lateral	3° ± 3	4° ± 3	-1° (-3 to 0.2)	0.08
Functional outcomes					
7- year follow-up	Limitation in prosupination	5° ± 11	5° ± 8	0.3° (-3 to 4)	0.86
	QuickDASH	5.8 ± 11	3.4 ± 5	2.4 (-1.0 to 5.8)	0.16
	ABILHAND	41 ± 2	42 ± 1	-0.5 (-1.1 to 0.8)	0.09
	Cosmetics (patient)	8.3 ± 2	7.8 ± 3	0.5 (-0.4 to 1.4)	0.29
	Cosmetics (clinician)	8.7 ± 2	8.1 ± 2	0.6 (-0.2 to 1.4)	0.17
	Hand grip strength %	99 ± 21	100.0 ± 18	-1.8 (-9.6 to 6.0)	0.64

[a]Data in these rows are from a prior publication [9]; PA = posteroanterior

Table 3. Radiographic and functional results (malunion vs acceptable alignment group)

		Malunion group (n=13)	Acceptable alignment group (n=115)	Mean difference (95% CI)	p value
Radiographic outcomes					
Consolidation[a]	Radius - PA	15° ± 7°	6° ± 4°	9.6° (4.0° to 15°)	< 0.001
	Radius - lateral	17° ± 6	9° ± 8	7.2° (1.5 to 13)	0.01
	Ulna - PA	7° ± 5	6° ± 4	1.6° (-1.2 to 4.3)	0.26
	Ulna - lateral	10° ± 7	6° ± 5	3.4°(-1.0 to 6.9)	0.06
		(n = 11)	**(n = 94)**		
7-year follow-up	Radius - PA	5° ± 3	5° ± 3	-0.1° (-2.4 to 2.1)	0.91
	Radius - lateral	4° ± 3	4° ± 3	0.3° (-1.7 to 2.3)	0.76
	Ulna - PA	5° ± 3	5° ± 3	0.01° (-2.2 to 2.2)	0.99
	Ulna - lateral	1° ± 2	4° ± 4	-2.8° (-5.2 to -0.4)	0.02
Functional outcomes		**(n = 11)**	**(n = 94)**		
7-year follow-up	Limitation in prosupination	6° ± 16	5° ± 9	0.8° (-5.2 to 6.9)	0.87
	QuickDASH	3.4 ± 6	4.6 ± 9	-1.3 (-6.8 to 4.2)	0.64
	ABILHAND	41 ± 2	41 ± 2	0.01 (-1.0 to 1.1)	0.98
	Cosmetics (patient)	8.0 ± 2	8.3 ± 2	-0.2 (-1.5 to 1.1)	0.58
	Cosmetics (clinician)	8.6 ± 1	8.7 ± 2	0.2 (-1.0 to 1.4)	0.76
	Hand grip strength %	98 ± 15	99 ± 20	-1.0 (-14 to 12)	0.88

[a]Data in these rows are from prior publication [9]; PA = posteroanterior.

Table 4. Multivariable logistic regression analysis

Subgroup	≥ 20° of limitation	Odds ratio (95% CI)	p value
Malunion group	27 (3 of 11)	5.2 (1.0-27)	0.045
Nonmalunion group	7 (7 of 94)		
Refracture	33 (3 of 9)	7.1 (1.4-37)	0.02
No refracture	7 (7 of 96)		

Factors associated with limitation in forearm rotation of ≥20° at minimum 5-years follow-up.

Part II

Long-term follow-up of diaphyseal forearm fractures

Chapter 4

Improved forearm rotation even after early conversion to below-elbow cast for non-reduced diaphyseal both-bones forearm fractures in children: a secondary 7.5-year follow up of a randomized trial

Linde Musters
Leon W. Diederix
Pim P. Edomskis
Kasper C. Roth
Joyce L. Benner
Gerald A. Kraan
Jan H. Allema
Max Reijman
Denise Eygendaal
Joost W. Colaris

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ABSTRACT

Background and purpose A previous RCT compared short-term results of above elbow cast (AEC) with early conversion to below elbow cast (A–BEC) in children with non-reduced diaphyseal both bone forearm fractures. After 7 months both groups had comparable function. We aimed to investigate whether forearm rotation improves or worsens over time.

Patients and methods We performed a long-term follow-up of a previous RCT. All patients were invited again for the long-term FU measurements. Primary outcome was limitation of forearm rotation. Secondary outcomes were loss of flexion and extension of the elbow and wrist compared with the contralateral forearm, the ABILHAND-kids questionnaire and the DASH questionnaire, JAMAR grip strength ratio and radiological assessment. The original RCT was registered in ClinicalTrials.gov with registry identifier NCT00314600.

Results The mean length of follow-up was 7.5 (4.4–9.6) years. Of the initial 47 children, 38 (81%) participated. Rotation improved in both groups over time, with no significant difference in the final forearm rotation 8.1^{o} (SD 22) for the AEC group and 8.3^{o} (SD 15) for the A–BEC group with a mean difference of –0.2 (95% confidence interval –13 to 12). Secondary outcomes showed no statistically significant differences. Finally, children < 9 years almost all have full recovery of function.

Conclusion Long-term follow-up showed that loss of forearm rotation after a non-reduced diaphyseal both bone lower arm fracture improved significantly compared with that at 7 months, independent of the initial treatment and children aged < 9 will have almost full recovery of function. This substantiates that the remaining growth behaves like a 'friend' at long-term follow-up.

INTRODUCTION

Forearm fractures of both bones account for 40% of all pediatric fractures(1). They are more common in boys and 20% of these fractures are located in the diaphysis. Usually non reduced diaphyseal forearm fractures of both bones are treated with an above elbow cast (AEC) for 6 weeks, and in selective cases converted to below elbow cast (BEC) for the last weeks. In case of instability of (1 of) the fractures after reduction, intramedullary nails or plates are advocated to stabilize the fracture(s)(2).
Previous studies showed a persisting loss of forearm rotation of up to 15% of the normal range of motion, especially in diaphyseal-located fractures(3). The underlying mechanism seems to be malunion of the radius and/or the ulna, combined with soft tissue contractures such as the interosseous membrane(4). This leads to the suggestion made by Colaris et al. that early conversion to BEC in the treatment of children with non-reduced diaphyseal forearm fractures of both bones could potentially result in less contractures of the interosseous membrane. Furthermore, this group also shows less remaining loss of forearm rotation 18° (SD 17) compared with 23° (SD 22) in the AEC group, but this was not statistically significant. This short-term follow-up showed positive results, but a long-term follow-up was missing(5). Previous studies already demonstrated relationship between age and the ability to correct bony deformities. Although both groups already showed good results in function at short-term follow-up, it is interesting to see if remaining growth in these 2 groups behaves like a 'friend or an enemy'. We aimed to evaluate the results of these 2 treatment groups. Our focus was on the primary outcome, loss of forearm rotation. Secondary outcome measures were loss of flexion and extension of the elbow and wrist, patient-reported outcomes measures (ABILHAND-kids questionnaire and quick DASH questionnaire, grip strength (JAMAR) ratio and radiological assessment (6).

PATIENTS AND METHODS

Our study is a long-term follow-up of a previous RCT. All 47 patients who had been previously included in the RCT by Colaris et al. (5) between January 2006 and August 2010, were invited to visit the outpatient clinic for additional clinical and radiological assessment. This population consisted of patients who were included after they visited the emergency department of 1 of 4 participating hospitals: Erasmus Medical Center (Rotterdam), HAGA Hospital (The Hague), Reinier de Graaf Hospital (Delft), and Franciscus Gasthuis and Vlietland Hospital (Rotterdam). Inclusion criteria were all children <16 with diaphyseal both bone forearm fractures with no indication for reduction, based on the below-set criteria, see Table 1. These children have been randomized for the previous study to treatment with 6 weeks of above elbow cast (AEC) or early conversion to below elbow cast (A–BEC), which means 3 weeks of above elbow cast

followed by 3 weeks of below elbow cast. The minimum follow-up was set at 5 years.
This study complies with the CONSORT statement (see Figure 1).

Outcome measures
Our primary outcome was a change in loss of forearm rotation in comparison with the contralateral side. Secondary outcome measures were change in loss of flexion extension of the elbow and wrist compared with the contralateral forearm, the Dutch version of the DASH and ABILHAND-kids questionnaire, grip strength (using a JAMAR dynamometer) displayed as a ratio of affected forearm/ contralateral side and radiological assessment of the radius and ulna. An independent orthopedic surgeon (LD) measured the forearm rotation, flexion and extension of the elbow and wrist in a standardized manner with the use of a goniometer. Before each measurement, the examiner ensured that the child was standing in an upright position. Meanwhile, the elbow was positioned firmly against the torso to eliminate compensating forearm rotation by using movements of the elbow and shoulder. The elbow was flexed in 90° with the forearm in mid-position and the wrist in neutral. Grip strength was determined using a JAMAR dynamometer on both sides and calculating a ratio of grip strength of the affected forearm / contralateral side and furthermore patients were asked to fill in the DASH and the ABILHAND-kid's questionnaires. The radiological assessment included measurement of the coronal and sagittal angulation of the radius and ulna conducted by 1 of the authors (PE). Analyses were done using locally available analysis programs such as PACS and JiveX.

Statistics
We compared the baseline characteristics and functional outcome at 7 months and at 7.5 years between the included patients and those lost to follow-up to rule out potential effects of attrition. Long-term results of primary and secondary outcomes were compared between the 2 groups (AEC vs. A–BEC) using independent T-testing and crosstabs. Results are presented as a mean with a 95% confidence interval (CI) and standard deviation (SD) because of a normal distribution. Furthermore, to address the issue of missing data, linear mixed model analyses were done for the primary outcome to compare the between-group differences over the different time points where means with 95% CI are presented.
To assess the interrater reproducibility of radiographic assessment 2 authors (PE and LD) measured angulations of the radius and ulna of 25 cases in coronal and sagittal view (at cast removal, at 7 months, and at 7.5-year follow-up).
We performed a subgroups analysis for both groups on loss of forearm rotation. The pronation and supination were scaled using the grading system as described by Daruwalla with excellent, good, fair and poor results for, respectively, 0–10°, 11–20°, 21–30°, and ≥ 31° of limitation(7).
All statistical analyses were performed using IBM SPSS Statistics version 23.

Ethics, registration, consent, data sharing, funding, and disclosures

The original RCT was registered in ClinicalTrials.gov with registry identifier NCT00314600. For this post-trial follow-up study ethics approval was again obtained at the regional medical ethical committee NL41839.098.12. This study complies with the CONSORT statement (Figure 1). Informed consent was again obtained for participation from parents of children < 16 years and from all patients aged ≥ 12 years. This research didn't receive grants from any funding agency in the public, commercial or not-for-profit sectors. None of the authors report any conflict of interest. Completed disclosure forms for this article following the ICMJE template are available on the article page, doi: 10.2340/17453674.2023.18340.

RESULTS

Between January 2006 and August 2010, 47 children were included in an RCT by Colaris et al. 38 patients responded and were clinically and radiologically assessed for long-term follow-up. The mean length of follow-up was 7.5 (4.4–9.6) years. 17 out of 23 patients who were allocated to AEC and 21 out of 24 patients who were allocated to A–BEC were finally included for follow-up. Baseline characteristics were similar between the groups (Table 2). In the AEC group 2 patients were excluded for a re-operation and 4 did not respond to invitation and in the A–BEC group 1 patient was reoperated and 2 did not respond to invitation. None of the patients had a re-fracture. To rule out potential effects of attrition we did a representability analysis. The included population was compared with the loss to follow-up population. This analysis showed no significant difference in age, sex, forearm rotation or secondary outcomes as ABILHAND-kids questionnaire, VAS and complication rate, concluding that the follow-up group was representative for the whole original study group (Table 3).

Our primary outcome, loss of forearm rotation, showed improvement in both groups over time, with no significant difference between the 2 groups. The AEC group went from a mean loss of rotation of 30° (SD 29) at 2 months follow-up, to 23° (SD 22) at 7.2 months to 8.1° (SD 22) at 7.5 years follow-up. The A–BEC group went from 31° (SD 24) loss of forearm rotation at 2 months, to 18° (SD 17) at 7.2 months, to 8.3° (SD 15) at 7.5 years follow-up. There was no significant difference between both groups at 7.5 years follow-up. Subgroup analyses based on the amount of loss of rotation showed no significant difference in mean limitation of pro-supination (Table 4).

To address missing data, linear mixed model analyses were performed, which showed a decrease in loss of forearm rotation over time in both groups. In the A–BEC group, a significant decrease was found when comparing 2 months loss of rotation to 7 months ($P = 0.02$), and 7 months to 7 years ($P < 0.001$).

Secondary outcomes (loss of flexion extension of the elbow and wrist, PROM's and grip strength) revealed no statistically significant differences between the 2 treatment groups

(Table 4).
At long-term follow-up we found no statistically significant differences in radiological outcomes between the 2 groups. There was an increase of the coronal radial angulation observed in both groups over time and an increase in maximal bowing (Table 6). Linear mixed model analyses showed significant increase in the AEC group of radial coronal angulation ($P < 0.001$) and bowing ($P < 0.001$) and significant decrease in radial sagittal angulation ($P = 0.001$). For the A–BEC group only significant decrease in sagittal radial angulation was found ($P = 0.007$).
We also performed a subgroup analysis comparing 2 subgroups: age < 9 years and ≥ 9 years, combining AEC and A–BEC groups. Our study showed a remaining mean loss of forearm rotation of 28.7 in patients ≥ 9 years of age after 7.5 years, compared with 4.9° in children < 9 years of age (mean difference -23.8 with 95%CI -38- to -9.0). There was a significantly more improvement of function in patients <9 years of age to almost no impairment. Almost all patients indifferent of age improved their function over time.

DISCUSSION

Our study demonstrates that early conversion to BEC in children with a non-reduced forearm fracture of both bones is also safe at long-term follow-up of 7.5 years. In accordance with the short-term follow-up, long-term follow-up of 7.5 years again showed no clinically relevant differences in either clinical or radiological aspect between treating non-reduced minimally displaced diaphyseal both bone forearm fractures in children with conventional AEC or with an early conversion to BEC. Both groups showed equal improvement in function with minimal persisting loss of rotation at long-term follow-up.
Secondary outcomes showed no statistically significant differences between the 2 groups for PROM's or radiological angulations. However, it did show a significant decrease over time for radial angulation in sagittal views for both groups, which is probably due to the excellent capacity to remodel over time.
Overall, this is a relatively favorable group, for they have little displacement with no need for reduction and with that, they have little risk of malunion and rotation limitation. This is in contrast to the dislocated group that often re-dislocate and cause malunion or rotation problems, resulting in more intramedullary nailing (8).
The remarkable increase of the coronal radial angulation and maximal bowing after 7.5 years in both groups can be explained by the natural increase of angulation of the radius in children (9). Firl et al. showed that the mean location of the maximal bowing was 60% of the total radial length. The mean maximum radial bow was 7.2% of the total radial length. The length of the radius and the maximum bowing increases with age, while the site of maximum radial bowing (x/y x 100) remains constant therefor the maximum radial bowing will increase with age (10). Another study by Weber et al. in 2019 compared 211 cadaveric specimens in humans

and their mean location of the maximal bowing was 45% of the radial length with a maximum radial bow 3.8% of the total radial length (11). But more important is to know how much radial bowing is accepted before function is impaired. Recent study by Wongcharoenwatana et al. showed that children with a mean radial bow of less than 6.8% can result in < 70° forearm pronation ($p=0.03$) and a mean radial bow of less than 5.8% can result in < 80° forearm supination ($p=0.02$). They suggest that mean radial bow should be restored to approximately 6–7% for optimal forearm rotation after fracture reduction. The location of the radial bow shows no significant correlation with the amount of pro/supination limitation (12).

Previous research

A systematic search of literature on previous long-term follow-up studies for pediatric forearm fractures resulted in less than 15 studies in total, and none of them was an RCT. Most studies were published more than 5 years ago and half of the studies were case reports. Therefore, our prospective randomized multi-center study presenting long-term results on diaphyseal pediatric forearm fractures is unique and important base for substantiated statements on how to treat these fractures.

To understand why early conversion to below elbow cast is just as good as above elbow cast in treating pediatric both bone forearm fractures when looking at loss of forearm rotation, it is important to understand which factors could possibly influence forearm rotation. Previous studies addressed several factors involved: malunion of the radius and/or the ulna (10) or contractures of the soft tissue (18). Rotational malunion affects motion directly whereas angulation and translational malunion indirectly limits pro- and supination. Soft tissue contractures (muscle, tendon, capsule, interosseous membrane, etc.) from injury, fracture healing and immobilization can also reduce the rotational arc of motion.

Colaris et al. showed that association of a re-fracture and a diaphyseal location are both risk factors for loss of forearm rotation with respectively an odds ratio of 14.1 and 2.7. Furthermore, intervention of a physiotherapist resulted in a decrease of loss of forearm rotation, which suggest that reversible soft tissue contractures might be of influence in the loss of rotation (19).

Our study showed a remaining loss of forearm rotation of 29° in patients ≥ 9 years of age. When looking at individual cases, 2 out of 5 cases ≥ 9 years had severe malunions with 85° and 47° loss of forearm rotation. The first case needed a correction osteotomy and the second case had a boney bridge. The group < 9 years had a remaining loss of forearm rotation of 4.9°, with 86% (25/29 patients) improving over time. There is a significantly less loss of pro-supination in the group < 9 years and almost all children had recovery of function over time. The degree of correction by growth is dependent on the remaining growth and the location and plane of the displacement. Early studies already demonstrated a significant relationship between age and the ability to correct deformity. Moesner and Ostergaard suggested that children under 9 years of age are able to achieve correction of 90% of their malunion and remodeling capacity decreases with age > 9 years (20). Höström et al. also showed that older children are less able

to compensate for fracture deformities and show more remaining loss of forearm rotation(21). Important is to know if this remaining loss of forearm rotation had any influence in daily life. Previous study by Morrey et al. showed that a minimum of 100° of forearm rotation (50° of pronation and 50° of supination) is needed to perform without limitation in daily life (22). However, later studies showed that more flexion and more pronation is necessary for daily activities as result of the increased use of cellular phones and tablets.
A malunion which is located near the more active distal physis has the highest capacity to remodel. The diaphyseal part has the lowest capacity for correction (17). Furthermore, angulation in the sagittal plane is better tolerated than angulation in the coronal plane and rotational malunion does not remodel at all (23). A recent study by Barvelink et al. published in 2020, showed no association between lower arm fractures with angulation and remaining motion deficit at 1 year follow-up (24). Bot et al. in 2011 showed that functional impairment after a diaphyseal forearm fracture correlates better with subjective and psychosocial aspects of illness, such as pain and pain catastrophizing, than with objective measurements of impairment (DASH, wrist and elbow function, forearm rotation), radiographic angulation or grip strength (3). This is comparable with our study, which showed no relation between PROM's and the amount of loss of forearm rotation in both groups.

Study limitations
Primary limitation was the inevitable non blinding of the clinical assessment. Again, at long-term follow-up the initial cast morphology revealed which group the patients were in. However, radiological assessments again were blinded.
Secondly, this study was conducted with a small sample size of only 33 patients of the 47 primarily included patients. But with a follow-up percentage of 70%, in this young population with a relatively long follow-up period, this is a good response. Furthermore, a previous study showed that when cases are missing at random or completely at random, up to 60% loss to follow-up is acceptable, without influencing the outcome (25). Thereby previous studies suggested that up to 40% loss to follow-up results in minimal attrition of the results (12). To expose any potential effects of attrition we did a representability analysis comparing the included and loss to follow-up groups, which showed the follow-up group was representative for the whole original study group (Table 3).

CONCLUSION

Long-term follow-up after an average of 7.5 years supports the previous suggestion in 2013 that early conversion to BEC compared with AEC as a treatment for children with non-reduced diaphyseal both bone fractures of the forearm show no significant differences between the 2 groups in loss of forearm rotation. Subgroup analyses show that children <9 years of age have more remodeling potential. Both treatment groups show almost full remodeling with a remaining loss of 8° of final forearm rotation without any functional impairment in daily life. This substantiates that the remaining growth behaves like a 'friend' at long-term follow-up.

AUTHOR CONTRIBUTION

LM writing, data analysis, submitting; LD writing, data analysis; KR data analysis, JB statistics; GR reviewer, data collecting; JA reviewer, data collecting; MR reviewer, writing, statistics; DE reviewer, writing; JC reviewer, writing.

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Table 1. Criteria for reduction of the fracture of radius and/or ulna based on anteroposterior and/or lateral radiographs

Type of displacement	Age in years	Displacement in °
Angulation	< 10	> 15
	10 - 16	> 10
Translation	< 16	>half of bone diameter
Rotation	< 16	> 0

Table 2. Representability of the lost to follow-up and included population. Values are mean (SD) unless otherwise stated

Factor	Lost to FU	Included	Mean difference (CI)
Number of patients	9	38	/
Mean age at trauma, range	6.2 (1.8–12.3)	6.4 (0.9–14.9)	–0.3 (–2.8 to 2.3)
Male sex, n	5	18	/
Forearm rotation at 7 months, °	135 (30)	130 (26)	4.6 (–15 to 25)
Loss of forearm rotation, °	19 (22)	21 (19)	–2.2 (–20 to 15)
ABILHAND-kids score [a]	42 (0)	41 (7.8)	1.5 (-5.7 to 8.7)
VAS-cosmetics parents/ child [b]			
parents/ child	7.4 (2.7)	7.9 (2.6)	–0.5 (–2.5 to 1.5)
surgeon	8.5 (1.3)	7.9 (2.2)	0.6 (–0.9 to 2.2)
Complications, %	0.2 (0.4)	0.4 (0.5)	–0.1 (–0.5 to 0.2)

CI = 95% confidence interval

[a] *ABILHAND-kids questionnaire score 0–42. 42 is optimal score.,*

[b] *VAS score 0–10. 10 is optimal score.*

Table 3. Baseline characteristics of the population non-reduced diaphyseal forearm fractures. Values are number of patients unless otherwise specified

Baseline	Total	AEC	A–BEC
Number of children	38	17	21
Mean age at trauma [a]	6.4 (0.9–14.9)	6.1 (2.1–14.3)	6.7 (0.9–14.9)
Length of FU [a]	7.5 (4.4–9.6)	7.8 (5.9–9.6)	7.2 (4.4–8.8)
Male sex	18	10	8
Dominant arm	17	9	9
Type fracture radius			
Buckle fracture	0	0	0
Greenstick	27	13	14
Complete fracture	11	4	7
Type fracture ulna			
Buckle	0	0	0
Greenstick	25	11	14
Complete fracture	13	6	7

AEC= above elbow cast.

BEC= AEC with early conversion to below elbow cast.

[a] Values in years are mean and (range).

Table 4. Loss of forearm rotation of the fractured arm with subgroup analysis. Values are number of patients unless otherwise stated

Time after trauma Loss of forearm rotation	AEC	BEC	Mean difference (CI)	P value
2 months	**n=23**	**n=24**		
None	3	2		
1–10°	5	3		
11–20°	3	5		
21–30°	2	5		
>31	10	9		
Limitations [a]	30 ° (29)	31 ° (24)	–0.9 (–17 to 15)	0.9
7.2 months	**n = 23**	**n = 24**		
None	6	6		
1–10°	4	4		
11–20°	2	6		
21–30°	3	3		
>31°	8	4		
Limitations [a]	23 ° (22)	18 ° (17) [b]	5.2 (-6.5 to 17)	0.4
7.5 years	**n = 17**	**n = 21**		
None	10	9		
1–10°	4	7		
11–20°	1	1		
21–30°	1	2		
>31°	1	2		
Limitations a	8 ° (22)	8 ° (15) [b]	–0.2 (–13 to 12)	1.0

AEC= Above elbow cast. BEC= AEC with early conversion to below elbow cast. CI = 95% confidence interval.
[a] Values are mean (SD)
[b] Significant change over time compared with the previous value in time (linear mixed-models analysis)

Table 5. Data on primary and secondary outcomes at 7.5-year long-term follow-up of non-reduced diaphyseal forearm fractures. Values are mean (SD)

Factor	AEC (n = 17)	BEC (n = 21)	Mean difference (CI)
Age at follow-up, years	13.9 (3.6)	13.9 (3.9)	0.0 ° (–2.5 to 2.5)
Loss of forearm rotation	5.7 ° (8.9)	1.5 ° (6.0)	4.1 ° (–1.5 to 9.8)
Range of motion forearm rotation	152 ° (28)	152 ° (18)	–0.8 ° (–16 to 15)
Loss of wrist flexion-extension	0.6 ° (2.5)	0 ° (0)	0.6 ° (–0.7 to 2.0)
Loss of elbow flexion-extension	0.0 ° (0)	0 ° (0)	/
ABILHAND-kids questionnaire [a]	41 (3.6)	40 (7.4)	0.9 ° (–3.2 to 5.0)
DASH score [b]	8.2 (11)	7.6 (14)	0.6 ° (–8.0 to 9.2)
%	1.0 (0.17)	0.96 (0.19)	0.1 ° (–0.1 to 0.8)

AEC= Above elbow cast. BEC= AEC with early conversion to below elbow cast. CI = 95% confidence interval.
[a] ABILHAND-kids questionnaire score 0-42. 42 is optimal score.
[b] DASH score 0–100, 100 being the worst score.
[c] JAMAR ratio = grip strength affected wrist/collateral side.

4

Table 6. Data on radiological outcomes, angulation at final follow-up. Values are mean (SD) unless otherwise stated

	AEC				BEC				7.5-year mean difference
Factor	Trauma	6 weeks	7.2 months	7.5 years	Trauma	6 weeks	7.2 months	7.5 years	Mean difference (CI)
AP radius, °	7 (4)	5 (4)	4 (4)	10 (2) [a]	8 (6)	8 (6)	7 (6)	10 (3)	–0.2 (–1.9 to 1.6)
AP ulna, °	6 (3)	5 (4)	5 (4)	5 (3)	8 (7)	6 (5)	5 (4)	4 (3)	1.2 (–0.9 to 3.3)
Lateral radius, °	11 (5)	11 (5)	9 (4)	4 (2) [a]	15 (11)	13 (7)	11 (6)	4 (3) [a]	–0.9 (–2.9 to 1.0)
Lateral ulna, °	11 (6)	5 (4) [a]	4 (4)	4 (3)	11 (12)	7 (5) [a]	7 (5)	5 (2)	0.8 (–2.0 to 1.1
Max. bowing radius			6 (1)	12 (2) [a]			7(3)	11(2)	0.8 (–0.6 to 2.3)

AEC= Above elbow cast. BEC= AEC with early conversion to below elbow cast. CI = 95% confidence interval.
[a] Significant change over time compared with the previous value in time (linear mixed-models' analysis).

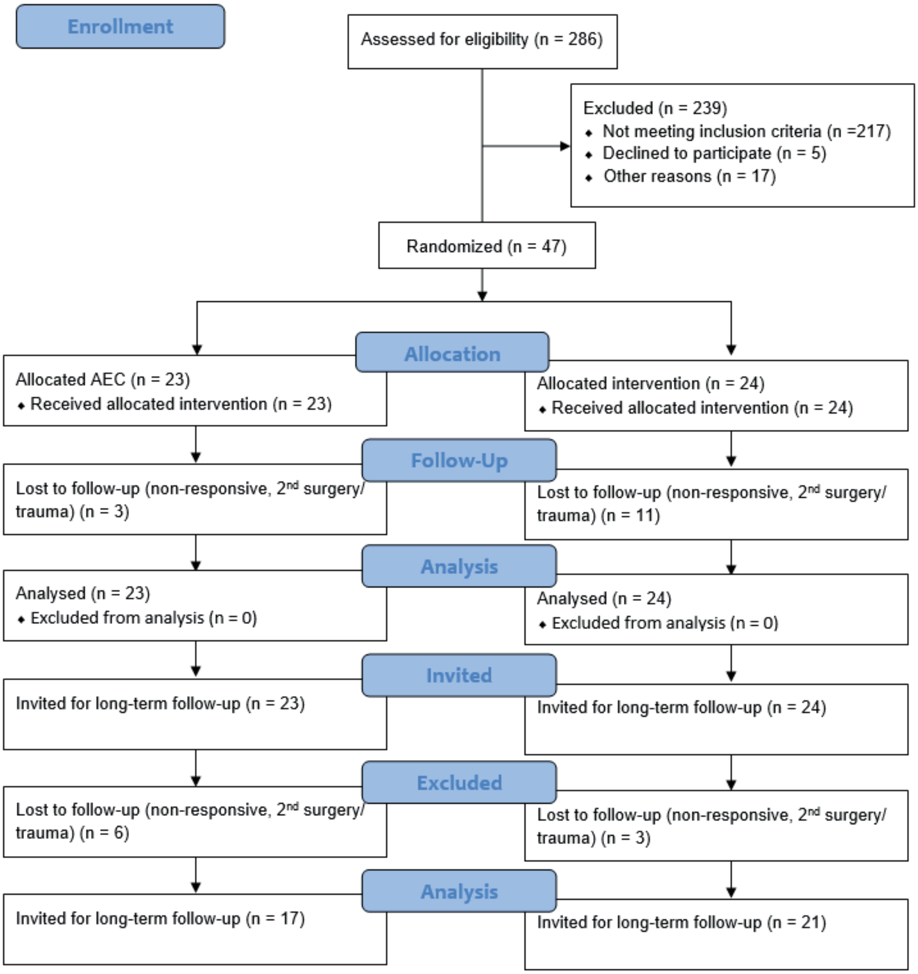

Figure 1. Consort patient flow diagram. Intervention was above elbow cast (AEC) with early conversion to below elbow cast (A–BEC)

Chapter 5

Does early conversion to below-elbow casting for pediatric diaphyseal both bones forearm fractures adversely affect patient-reported outcomes and range of motion?

Linde Musters
Kasper C. Roth
Leon W. Diederix
Pim P. Edomskis
Joyce L. Benner
Max Reijman
Denise Eygendaal
Joost W. Colaris

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ABSTRACT

Background For distal forearm fractures in children, it has been shown that a below-elbow cast is an adequate treatment that overcomes the discomfort of an above-elbow cast and unnecessary immobilization of the elbow. For reduced diaphyseal both-bone forearm fractures, our previous randomized controlled trial (RCT)—which compared above-elbow cast with early conversion to a below-elbow cast—revealed no differences in the risk of redisplacement or functional outcomes at short-term follow-up. Although studies with a longer follow-up after diaphyseal both-bone forearm fractures in children are scarce, they are essential for growth might affect the outcome.

Questions/purposes In this secondary analysis of an earlier RCT, we asked: (1) Does early conversion from an above-elbow to a below-elbow cast in children with reduced, stable diaphyseal forearm fractures result in worse clinical and radiological outcome? (2) Does a malunion result in inferior clinical outcomes at 7.5 years of follow-up?

Methods In this study we evaluated children at a minimum of 5 years of follow-up who were included in a previous RCT. The mean duration of follow-up was median 7.5 years (range 5.2 to 9.9). The patients for this RCT were included from the emergency departments of four different urban hospitals. Between January 2006 and August 2010, we treated 127 patients for reduced diaphyseal both-bone forearm fractures. All 127 patients were eligible; 24% (30) were excluded because they were lost before the minimum study follow-up or had incomplete datasets, leaving 76% (97) for secondary analysis. The loss the follow-up group was comparable to the included population. Eligible patients were invited for secondary functional and radiographic assessment. The primary outcome was the difference in forearm rotation compared with the uninjured contralateral arm. Secondary outcomes were the ABILHAND-kids and quick-DASH questionnaire, loss of flexion and extension of the elbow and wrist compared with the contralateral forearm, JAMAR grip strength ratio, and radiological assessment of residual deformity. The study was not blinded regarding the children, parents, and clinicians.

Results At 7.5 years follow-up, there were no differences in ABILHAND-kids questionnaire (above-elbow cast: 41 ± 2.4 versus above/below-elbow cast: 41.7 ± 0.7, mean difference -0.7 [95% confidence interval (CI) -1.4 to 0.04]; p = 0.06), QuickDASH above-elbow cast: 5.8 ± 9.6 versus 2.9 ± 6.0 for above-/below-elbow cast, mean difference 2.9 [95% CI -0.5 to 6.2]; p = 0.92), and grip strength 0.9 ± 0.2 for above-elbow cast versus 1 ± 0.2 for above/below elbow cast, mean difference -0.04 [95% CI -1 to 0.03]. Functional outcomes showed no difference in loss of forearm rotation for above-elbow cast 7.9 ± 17.7 versus 4.1 ± 6.9 for above-/below-elbow cast, mean difference 3.8 [95% CI -1.7 to 9.4]; p = 0.47, the arc of motion was 152° ± 21° for the above-elbow cast group and 155° ± 11° for the above/below-elbow cast group, mean difference -2.5 (95% CI -9.3 to -4.4; p = 0.17), loss of wrist flexion-extension in above-elbow cast group is 1.0° ± 5.0 versus 0.6° ± 4.2 for above/below-elbow cast, mean difference 0.4° [95% CI -1.5 to 2.2]; p = 0.69. The secondary follow-up showed improvement in forearm

rotation in both groups compared with the rotation at 7 months. For radiographical analysis, the only difference was in AP ulna (above-elbow cast: 6° ± 3° versus above/below-elbow cast: 5° ± 2°, mean difference 2° [1° to 3°]; p = 0.003), although this is likely not clinically relevant. There were no differences in the other parameters. Thirteen patients with persisting malunion at 7 months follow-up showed no clinically relevant differences in functional outcomes at 7.5-year follow-up compared with children without malunion. The loss of forearm rotation was 5.5 ± 9.1 for the malunion group compared with 6.0 ± 13.9 in the non-malunion group, with a mean difference of 0.4 (95 % CI of -7.5 to 8.4; p = 0.9).
Conclusion In light of these results, we suggest that surgeons perform an early conversion to a below-elbow cast for reduced diaphyseal both-bone forearm fractures in children. This study shows that even in patients with secondary fracture displacement, remodeling occurred. And even in persisting malunion these patients mostly showed good-to-excellent final results. Future studies, such as a meta-analysis or a large, prospective observational study, would help to establish the influence of skeletal age, sex, and the severity and direction of malunion angulation of both the radius and ulna on clinical result. Furthermore, a similar systematic review could prove beneficial in clarifying the acceptable angulation for pediatric lower extremity fractures.

Level of Evidence Level I, therapeutic study.

INTRODUCTION

Diaphyseal forearm fractures are far less forgiving than distal forearm fractures in the growing skeleton. Almost half of pediatric fractures are forearm fractures of both bones, with 20% of fractures located in the diaphysis [4, 5, 26]. Although there is an increasing tendency to treat diaphyseal forearm fractures with intramedullary nails, stable fractures after reduction can also be treated in an above-elbow cast [29]. The disadvantage of treatment in a cast remains fracture redisplacement, which has been described in up to 39% [20, 27, 29]. Redisplaced fractures that accepted and left untreated often result in a malunion [1, 5, 8, 9, 10, 11, 14, 17]. In general, these diaphyseal malunions demonstrate less remodeling capacity compared with distal forearm fractures. Such a malunion can result in rotational impairment caused by either collision of the forearm bones or tightness of the soft tissues as the central band of the interosseous membrane [1, 9, 13, 14, 18, 21, 25, 28].

A previous study by Colaris et al. [6] compared two groups of children with stable diaphyseal reduced both-bone forearm fractures. The first group was immobilized in an above-elbow cast for 6 weeks, and the second group was immobilized in an above-elbow cast for 3 weeks followed by 3 weeks of a below-elbow cast [17]. After 7 months, no difference was found in loss of forearm rotation and similar redisplacement proportion. Cast comfort was better in the above-/below-elbow cast group. For this is a population with incredible remodeling capacity and functional recovery, we believe that treatment recommendations should be based on the occurrence of complications and long-term functional outcomes.

Therefore, we performed a secondary analysis of data and conducted the following research questions (1) Does early conversion from an above-elbow to a below-elbow cast in children with reduced, stable diaphyseal forearm fractures result in worse clinical and radiological outcome? (2) Does a malunion result in inferior clinical outcomes at 7.5 years of follow-up?

PATIENTS AND METHODS

Trial Design and Participants

This was a secondary analysis with clinical follow-up (with a minimum of 5 years) of a previous RCT by Colaris et al. [6]. Children younger than 16 years of age who visited the emergency department of one of four participating Dutch hospitals: Erasmus Medical Center (Rotterdam), HAGA Hospital (The Hague), Reinier de Graaf Hospital (Delft), and Franciscus Vlietland Hospital (Schiedam), were eligible for participation. This study complies with the CONSORT statement (Fig. 1).

Participants

We approached the 127 patients who were included between January 2006 and August 2010.

All patients were invited to visit the outpatient clinic for clinical and radiological reassessment between January 2014 and April 2017. Children younger than 16 years of age were eligible for the initial RCT if they presented with a displaced, diaphyseal, both-bone forearm fracture that was stable after reduction. A fracture was defined as unstable if full pronation and supination of the proximal forearm caused redisplacement of the fracture under fluoroscopic vision. This test for stability has been used before in a group of children with forearm fractures [7]. The exclusion criteria were: no response to our invitation for follow-up, refracture, or secondary surgery of the affected forearm. At 7 years, follow-up measurement and informed consent were obtained from all children and parents of children aged younger than 12 years. We considered 127 as potentially eligible. Based on that, 100% (127) were eligible; 24% (30) were excluded because they were lost before the minimum study follow-up or had incomplete datasets, leaving 76% (97) for secondary analysis. The loss the follow-up group was comparable to the included population (Supplemental Table 1; supplemental materials are available with the online version of CORR®).

Interventions

For the initial study, a surgeon reduced the fracture in the operating room under general anesthesia with fluoroscopic guidance. The fracture was checked for stability, if unstable the patient was excluded and treated with intramedullary nails. The remaining fractures were defined as stable and the patients were randomized to 6 weeks of AEC or to 3 weeks of AEC followed by 3 weeks of BEC. All casts were applied the same way, following a protocol set up by the research group. Clinical and radiographic evaluation happened at 1, 3, and 6 weeks after initial trauma. Fracture displacement, as defined by the loss of reduction according to the primary reduction criteria (Supplemental Table 2; supplemental materials are available with the online version of CORR®), required new fracture reduction. Finally, the cast was removed 6 weeks after initial treatment. At 2 and 6 months after the initial trauma, patients were assessed for clinical and radiological outcome. For prosupination, two different methods were used: visual estimation and conventional goniometry. For the visual measurement, the elbow was held in 90° flexion against the body, an estimate was made by two examiners (JC,LD). For the goniometer, a 180° protractor goniometer with two movable arms was used and both examiners performed three independent measurements, which they averaged.

Children with more than 30° of functional impairment at the 2-month examination were referred to a physiotherapist. At the 7-year mark, all patients who consented to follow-up were invited to the clinic for clinical and radiological evaluation.

Descriptive Data

Seventy-six percent (97 of 127) of patients with stable reduced diaphyseal both-bone forearm fracture were included in this secondary analyses. Forty-eight percent (47 of 97) had an above-elbow cast and 52% (50 of 97) had an above/below-elbow cast. The median (range) age in the above-elbow cast group was 16 years (9 to 24) and 15 (9 to 22) for the above-/below-elbow group. In both groups, 64% (30 of 47 and 32 of 50) were men/boys. The median length of follow-up of 7.6 (5.2 to 9.9) in the above-elbow cast group and 7.4 (5.2 to 9.8) in the above/below elbow cast group. There were no differences in baseline characteristics (Table 1).

Outcomes Measures and Outcomes Assessment

Our primary goal was to compare the difference in forearm rotation with the contralateral uninjured arm between the two groups. This outcome was also used in the initial RCT. We compared the outcomes at 7.5-years to the outcomes at 7 months of follow-up (Table 2).
Out secondary study goals were the loss of flexion-extension of the elbow and wrist compared with the contralateral forearm, the QuickDASH (score 0-100/higher representing worse function , MCID 15.9 to 20 points) ABILHAND-kids questionnaire (score 0-42/higher score represents better function), grip strength (measured with a Jamar Dynamometer) displayed as a ratio of affected forearm/contralateral side, and radiological assessment of the angulation of radius and ulna [8, 15, 17–19, 21]. One orthopaedic surgeon (LWD) performed the unblinded standardized physical examination (Table 3). Finally, we performed a radiological assessment on radiographs at the final follow-up, where we measured the coronal and sagittal angulation of the radius and ulna (Table 4). Different cutoff values were used to define a malalignment for different ages (Fig. 1). Radiological measurements were conducted in a blinded fashion by one of the coauthors (PPE) [12, 15, 23, 30]. Analyses were done using locally available analysis programs (PACS and JiveX). Finally, we performed a sub analysis where we looked at the same primary and secondary outcomes but compared the malunion group to the non-malunion group.

Ethical Approval

We obtained ethical approval for this study from Erasmus University Medical Centre, Rotterdam, the Netherlands (Protocol number NL41839.098.12). The original RCT was registered in ClinicalTrials.gov with registry identifier NCT NCT00398242.

Statistical Analysis

To evaluate whether the patients included in the current study are representative of the total initial study population and to address the potential effects of attrition, we performed a sensitivity analysis. We compared the baseline characteristics, functional outcomes, and complications at short-term follow-up (7 months) between the included patients (responders) and the patients lost to follow-up (nonresponders). We compared 7.5-year results of the primary and secondary outcome measures of the two treatment groups (above-elbow cast versus above-/below-elbow cast). Differences between both groups were analyzed using independent t-tests and chi-square tests. Results are presented as mean ± SD and p value or % (n) for categorial variables. In addition, we performed the Levene test for equality to compare

means. Finally, we conducted a linear mixed model analysis for multiple follow-up moments (moment of trauma, 6 weeks post-trauma, 7 months post-trauma, and 7.5 years post-trauma) in time to address possible missing data.
To assess the interrater reproducibility of radiographic assessment, two authors (PPE, LWD) measured the radiological angulations of 45 patients (at cast removal and final follow-up). The interrater reproducibility of the radiological assessment showed an intraclass correlation coefficient (ICC) of 0.8 (95% confidence interval [CI] 0.7 to 0.9) and 0.9 (95% CI 0.8 to 0.9) for the radioulnar angulation of the ulna and radius, respectively. The ICC of sagittal angulation was 0.9 (95% CI 0.9 to 1) for the ulna and 0.9 (95% CI 0.8 to 0.9) for the radius [7]. We performed statistical analyses using SPSS Statistics version 27 (IBM).

RESULTS

Clinical and Radiological Outcomes
This study showed no difference in clinical and radiological outcomes with early conversion to a below-elbow cast. At 7.5 years follow-up, the loss of forearm rotation was 7.9° ± 17.7 for the above-elbow cast group and 4.1° ± 6.9 for the above/below-elbow cast group, with a mean difference of 3.8° [95% CI -1.7 to 9.4]; p = 0.47). A mixed linear model analysis also showed improvement in forearm rotation over time for both groups. The above-elbow cast group improved from a mean loss of rotation of 27° ± 22° at 2 months to 18° ± 16° at 7 months to 8° ± 18° at 7.5 years (Table 2). For the above-/below-elbow cast group, this was 22° ± 19° at 2 months, 12° ± 12° at 7 months, and 4° ± 7° at 7.5 years.
There were no differences in the secondary outcome measures. The ABILHAND-kids questionnaire had similar results in both groups (above-elbow cast: 41 ± 2.4 versus above-/below-elbow cast: 41.7 ± 0.7, mean difference -0.7 [95% CI -1 to 0.04]; p = 0.06). The QuickDASH (above-elbow cast: 5.8 ± 9.6 versus 2.9 ± 6.0 for above-/below-elbow cast, mean difference 2.9 [95% CI -0.5 to 6.2]; p = 0.92), for loss of forearm rotation (above-elbow cast 7.9° ± 17.7 versus 4.1 ° ± 6.9 for above-/below-elbow cast, mean difference 3.8° [95% CI -1.7 to 9.4]; p = 0.47), for loss of wrist flexion-extension (above-elbow cast group is 1.0° ± 5.0 versus 0.6 ± 4 for above/below-elbow cast, mean difference 0.4 [95% CI -1.5 to 2.2]; p = 0.69), and for grip strength (0.9 ± 0.2 for above-elbow cast versus 1 ± 0.2 for above-/below-elbow cast, mean difference -0.04 [95% CI -1 to 0.03]; p = 0.24) also demonstrated no differences (Table 3).
For radiographical analysis, the only difference was in ulnar angulation in the coronal plane (above-elbow cast: 6° ± 3° versus above-/below-elbow cast: 5° ± 2°, mean difference 1.8° [0.7° to 3°]; p = 0.003), although that is likely not clinically relevant. Less ulnar angulation in the coronal view and more ulnar bowing (p < 0.001) were found in the above-/below-elbow cast group (p < 0.001) (Table 4). When we compared all time points, we found an increase in radial

angulation over time in the coronal view for the above-/below-elbow cast group ($p = 0.003$) but not for the below-elbow cast group.

Association of Malunion with Clinical Outcomes

Children with malunion showed more radial angulation in the sagittal plane at the final follow-up but no difference in clinical outcome. Accepted secondary displacement in the cast resulted in malalignment in 34 patients during the cast treatment; 22 patients still had a radiological malunion based on the previously set criteria, and 12 had remodeled at 7 months follow-up. Of the 22 patients with malunion, only one was lost to follow-up for the secondary measurements. At 7.5-years of follow-up, 13 of 22 patients still had a radiologic malunion, of which seven patients were in the above-elbow cast group and six patients were in the above-/below-elbow cast group. Thirteen patients with persisting malunion at 7 months of follow-up showed no clinically relevant differences in functional outcomes at 7.5-year follow-up compared with children without malunion. The loss of forearm rotation was 5.5° ± 9.1 for the malunion group compared with 6.0° ± 13.9 in the nonmalunion group, with a mean difference of 0.4° (95 % CI of -7.5 to 8.4; $p = 0.92$). Secondary outcomes showed no differences between the malunion and nonmalunion groups. The JAMAR ratio in the non-malunion group was 0.97 ± 0.2 compared with 0.94 ± 0.2 in the malunion group, with a mean difference of 0.04 (95% CI of -0.06 to 0.14; $p = 0.43$). The ABILHAND-kids questionnaire of 41.7 ± 0.5 in the malunion group compared with 41.4 ± 1.9 in the non-malunion group, with a mean difference of -0.3 (95% CI of -1.4 to 0.7; $p = 0.53$). The QuickDASH was 5.0 ± 6.4 in the malunion group compared with 4.2 ± 8.2 in the nonmalunion, with a mean difference of -0.8 (95% CI of -5.6 to 4.0; $p = 0.75$) (Table 5). Linear mixed analyses showed improvement in rotation over time ($p = 0.002$). Radiological analysis comparing the malunion with the nonmalunion group only showed a difference in radial angulation in the sagittal plane, 8.2 ± 4.0 in the malunion group compared with 4.3 ± 3.1 in the nonmalunion group, with a mean difference of -4.0 [95% CI of -5.9 to -1.9; $p < 0.001$] (Table 5).

DISCUSSION

Half of pediatric forearm fractures are both-bone forearm fractures, and 20% of these fractures are located in the diaphysis. Diaphyseal both-bone forearm fractures are known for their higher risk of secondary displacement and malunions because of the lower remodeling capacity [1, 5, 20, 27]. They currently are treated with 6 weeks in an above-elbow cast. Colaris et al. [7] showed that early conversion to a below-elbow cast results in more cast comfort with no increase in secondary dislocations. Children have a great remodeling capacity and capacity for functional recovery; we believe that treatment recommendations should therefore be based on the occurrence of complications and functional outcomes in the long term. Our secondary analysis of an earlier RCT shows that early conversion to a below-elbow cast should be the recommended treatment strategy for stable, reduced pediatric both-bone forearm fractures because there are no difference in functional and radiological outcome when compared to 6 weeks in an above-elbow cast. Even the secondary displaced malunions showed excellent clinical outcomes at 7.5 years despite the fact that 62% of the malunions were not fully corrected by growth.

Limitations

This study has some limitations. Primarily, the clinical assessment was not blinded. Blinding of patients was impossible because of the cast morphology. The second limitation is the number of patients lost to follow-up. To address the potential effects of attrition secondary to loss of follow-up, we did a patient-group analysis, showing that the loss-to-follow-up group was representative of the original study group.

Clinical and Radiological Outcomes

We found no differences between the groups at 7.5 years of follow-up in terms of patient-reported outcomes, ROM, or grip strength. Furthermore, we found no clinically important differences in radiological outcomes between the two groups. Because patients find the below-elbow cast more comfortable, we recommend that early conversion to a below-elbow cast should be the treatment of choice for children with stable, diaphyseal both-bone forearm fractures. We observed some differences in radiologic angulation between the two treatment groups, but none of these were clinically relevant. Regardless of the initial treatment, the radiological outcomes were good. This confirms findings from a study that reported good or excellent outcomes in 92% of patients who were treated with closed reduction and a cast [22]. In that series, results were graded as excellent if there were no complaints with physical activity and/or a loss of ≤ 10° of forearm rotation.

Association of Malunion with Clinical Outcomes

Children with malunion showed more radial angulation in the sagittal plane on radiographs at the most-recent follow-up, but this was not associated with poorer clinical outcomes. This supports our earlier recommendation to treat stable diaphyseal both-bone forearm fractures with an early conversion to a below-elbow cast, since even when they do secondarily displace, the pediatric skeleton seems very forgiving, and the radiographic finding does not seem to result in pain or loss of function.

The evidence shows that diaphyseal both-bone forearm fractures treated nonoperatively, either with a cast or with manipulation followed by a cast, have a high tendency to re-displace. Bowman et al. [3] retrospectively analyzed radiographs of 282 children with diaphyseal both-bone forearm fractures. Fifty-six percent (80) of children had their first radiographic evidence of redisplacement during the first week post reduction. The authors stated that patients

10 years or older and those with proximal-third radius fractures are at the highest risk for redisplacement. One study looked at risk factors for redisplacement in diaphyseal forearm fractures in 57 children [27]. They found that a poorer reduction (OR 8.5) and a complete fracture (OR 9.6) were factors associated with redisplacement [29].
Whether redisplacement and malunion causes important levels of functional impairment has been controversial. Our findings, based on a robust secondary analysis of an earlier RCT, suggests that these residual deformities are well tolerated. However, another prospective study evaluated the relationship between residual deformity and functional outcomes after closed treatment of displaced diaphyseal both-bone forearm fractures in 25 children, and found that loss of forearm rotation was correlated with the maximum angulation of the radius seen on either the final PA or lateral radiograph. Of the 25 patients, 20% (5) had malunions with more than 15° of angulation of either the radius or ulna; three of these patients demonstrated a more than 30° of loss of forearm rotation [31]. Our study also showed more angulation in the malunion group, but no correlation with more loss of rotation.
The evidence shows that some degree of forearm malunion can be accepted in children because the remaining growth in pediatric bones enables remodeling capacity. The degree of correction by growth depends on the remaining growth and the location and plane of the malunion. Earlier studies have demonstrated a relationship between age and the ability to correct the deformity. One study suggested that children younger than 9 years of age can achieve correction of 90% of their malunion, and remodeling capacity decreases with age older than 9 years [19]. Another study showed that the age at the time of the fracture was correlated positively with late residual angulation, older children being less able to compensate for the fracture deformity. Also, they showed a correlation between the late residual angulation and limitation of pronation and supination [14]. Another study showed that the closer to the growth plate, the higher the remodeling potential. The authors concluded that midshaft fractures in children older than 10 years of age with angulation have a poor diagnosis if left uncorrected [16]. But even when they don't remodel completely, these children seem generally to have good ROM. One study presented the outcomes of 39 children with malunions after severely angulated diaphyseal both-bone forearm fractures with a mean follow-up of 6 years. Complete remodeling occurred in only 12 of 39 patients, almost all younger than 10 years of age, but 92% showed good-or-excellent outcomes despite persisting radiological malunion [22]. Another study showed that most malunions in children result in complete functional recovery or minimal function loss with no influence in daily use [24]. In line with these studies, our secondary analysis of an RCT showed that even though patients with a malunion have more sagittal radial angulation at follow-up, all children remodeled to a clinically acceptable angulation, with good-to-excellent functional outcomes at final follow-up. Having said that, it is worth noting that despite the good final results, it might take years to gain full rotation and a cosmetically straight forearm. Therefore, we believe that children who develop unacceptable angulation following early redisplacement of unstable both-bone forearm fractures may benefit

from consideration of surgery, but this needs to be considered in light of its risks.

Conclusion

In light of these results, we suggest that surgeons perform an early conversion to a below-elbow cast for reduced stable diaphyseal both-bone forearm fractures in children. Even in patients with secondary fracture displacement, remodeling occurred, and with persisting malunion most patients showed good to excellent results at 7.5-year follow-up. In the future, meta-analyses or large prospective observational studies would be helpful to establish the influence of skeletal age, sex, and the severity and direction of malunion angulation of both the radius and ulna on clinical result.

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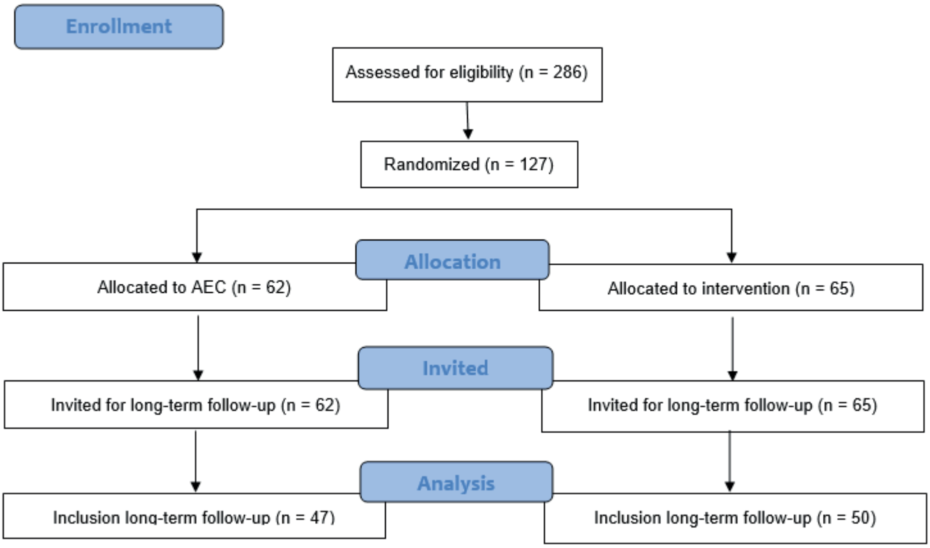

Fig. 1 This CONSORT flow diagram shows how patients were allocated in this study.

Table 1. Baseline characteristics of the study sample

Characteristic	Above-elbow cast (n = 47)	Above/below-elbow cast (n = 50)
Age at time of fracture in years	8 ±3	8 ± 3
Age at follow-up in years	16 ± 4	15 ± 31
Length of follow-up in years	7.6 ± 1.2	7.4 ± 1.4
Boys	64 (30)	64 (32)
Fracture type, radius		
Buckle	0 (0)	0 (0)
Greenstick	32 (15)	60 (30)
Complete	68 (32)	40 (20)
Fracture type, ulna		
Buckle	0 (0)	0 (0)
Greenstick	47 (22)	62 (31)
Complete	53 (25)	38 (19)

Data presented as mean ± SD or %(n).

Supplemental Table 1. Comparison of patients lost to follow-up with those who were accounted for and analyzed

	Lost to follow-up (n = 30)	Included (n = 97)	Mean difference (95% CI)	p value
Age at trauma in years	7.8 ± 3.7	7.9 ± 3.0	-0.04 (-1.4 to 1.3)	0.95
Boys	81 ± 25	64 ± 61		0.08
Loss of forearm rotation at 7 months in °	14.7 ± 13.7	14.6 ± 14.8	0.04 (-6.0 to 5.9)	0.04
Arc of motion at 7 months in °	132 ± 23	132 ± 18	-0.3 (-8.3 to 7.6)	0.94
ABILHAND-kids questionnairea	41.3 ± 1.5	40.1 ± 8.1	1.3 (-1.9 to 4.4)	0.43
VAS-cosmetics parents/childb	7.6 ± 2.4	8.3 ± 2.0	-0.7 (-1.6 to 0.2)	0.11
VAS-cosmetics surgeonc	8.1 ± 2.0	8.5 ± 1.9	-0.4 (-1.3 to 0.4)	0.29

Data presented as mean ± SD or % (n).
[a]ABILHAND-kids questionnaire score 0 to 42, higher score represent better function.
[b]VAS cosmetic parents/child score 0 to 10, higher scores represent better cosmesis.
cVAS cosmetic surgeon score 0 to 10, higher scores represent better cosmesis.

Table 2. Loss of forearm rotation of the fractured arm, subgroup analysis

Los of rotation	Above-elbow cast	Above/below-elbow cast	Mean diff with 95%CI	P-value
2 months after trauma	n = 62	n = 65		
None	6 (4)	14 (9)		
1-100	19 (12)	31 (20)		
11-200	26 (16)	18 (12)		
21-300	16 (10)	8 (5)		
>310	32 (20)	29 (19)		
Mean limitation in °	27 ± 22	22 ± 19	5.3 (-2 to 13)	0.15
7 months after trauma	n = 62	n = 65		
None	19 (12)	32 (21)		
1–100	19 (12)	28 (18)		
11–200	31 (19)	22 (14)		
21–300	12 (8)	11 (7)		
> 310	17 (11)	8 (5)		
Mean limitation in °	18 ± 16	12 ± 12	5.7 (0.6 to 11)	0.03
7.5 years after trauma	n = 47	n = 50		
None	49 (23)	58 (29)		
1–10	23 (11)	28 (14)		
11–20	21 (10)	12 (6)		
21–30	2 (1)	2 (1)		
> 31 degrees	4 (2)	0 (0)		
Mean limitation in °	8 ± 18	4 ± 7	4 (-2 to 9)	0.16

Data presented as mean ± SD or % (n).

Supplemental Table 2. Criteria for reduction of the fracture of radius and/or ulna

Type of displacement	Age in years	Deformity in °
Angulation	Younger than 10 10-16	> 15 > 10
Translation	Younger than 16	> 1/2 of bone diameter
Rotation	Younger than 16	> 0

Table 3. Data on primary and secondary outcomes at 7.5 years of follow-up

	Above-elbow cast (n = 47)	Above / below-elbow cast (n = 50)	Mean difference (95%CI)	p value
ABILHAND-kids questionnairea	41 ± 2.4	41.7 ± 0.7	-0.7 (-1.4 to 0.04)	0.06
Quick DASH scoreb	5.8 ± 9.6	2.9 ± 6.0	2.9 (-0.5 to 6.2)	0.92
JAMAR score (ratio)c	0.9 ± 0.2	0.9 ± 0.2	-0.04 (-1 to 0.03)	0.24
Loss of forearm rotation in °	7.9 ± 17.7	4.1 ± 6.9	3.8 (-1.7 to 9.4)	0.47
Arc of motion in °	152 ± 21	155 ± 11	-2.5 (-9.3 to 4.4)	0.17
Loss of wrist flexion-extension in °	1.0 ± 5.0	0.6 ± 4.2	0.4 (-1.5 to 2.2)	0.69
Loss of elbow flexion-extension in °	0 ± 0	0 ± 0		

Mean values have been rounded to either whole numbers or one digit to the right of the decimal point.
aABILHAND-kids questionnaire score 0 to 42, higher score represents better function.
bDASH score 0 to 100, lower score represents better function.
cJAMAR ratio = grip strength in the affected wrist/grip strength in the collateral side.

Table 4. Radiological analysis of angulation at 7 months compared with 7.5 years follow-up

	Above-elbow cast	Above/below-elbow cast	Mean (95% CI)	p value
7 months of follow-up	**n = 62**	**n = 65**		
AP radius in °	7 ± 5	5.5 ±4	1.5 (-0.7 to 3.0)	0.06
AP ulna in °	6 ± 4	6 ± 5	0.1 (-1.4 to 1.6)	0.90
Lateral radius in °	8 ± 5	8 ± 5	-0.4 (-2 to 1.4)	0.66
Lateral ulna in °	6 ± 5	4 ± 4	1.7 (0.2 to 3)	0.02
Bowing radiusa	12 ± 2	13 ± 2	-1 (-2 to 0.1)	0.08
7.5 years of follow-up	**n = 47**	**n = 50**		
AP radius in °	9 ± 2	9 ± 4	0.3 (-1.0 to 1.7)	0.61
AP ulna in °	6 ± 3	5 ± 2	1.8 (0.7 to 3.0)	0.003
Lateral radius in °	5 ± 3	5 ± 4	-0.1 (-1.5 to 1.4)	0.94
Lateral ulna in °	5 ± 3	5 ± 2	0.2 (-0.8 to 1.2)	0.70
Bowing radiusa	2 ± 2	13 ± 3	-1.6 (-2.7 to -0.5)	0.004

Data presented as mean ± SD.
aBowing is in %, calculated with the following formula; r/Y*100 [12].

Table 5. Outcome of subgroup with malunion at final follow-up compared with the group without malunion

	Malunion (n = 13)	No malunion (n = 84)	Mean difference (95% CI)	p value
Primary/secondary outcomes				
Loss of forearm rotation in °	6 ± 9	6 ± 14	0.4 (-7.5 to 8.4)	0.92
ABILHAND-kids questionnairea	41.7 ± 0.5	41.4 ± 2	-0.3 (-1.4 to 0.7)	0.53
QuickDASH scoreb	5.0 ± 6	4.2 ± 8	-0.8 (-5.6 to 4.0)	0.75
JAMAR score (ratio)c	0.94 ± 0.2	0.97 ± 0.2	0.04 (-0.06 to 0.1)	0.43
Radiologic analysis				
AP radius in °	9 ± 4	9 ± 3	-0.1 (-2 to 2)	0.93
AP ulna in °	5 ± 3	6 ± 3	0.3 (-1.5 to 2)	0.74
Lateral radius in °	8.2 ± 4	4.3± 3	-4 (-5.9 to -1.9)	< 0.001
Lateral ulna in °	5 ± 3	5 ± 2	-0.01 (-1.5 to 1.5)	0.99
Bowing radius %d	13 ± 3	13 ± 3	-0.5 (-2 to 1)	0.52

Data presented as mean ± SD.
aABILHAND-kids questionnaire score 0 to 42, higher score represent better function.
bQuick DASH score 0 to 100, lower score represents better function.
cJAMAR ratio = grip strength in the affected wrist/grip strength in the collateral side.
dBowing is in %, calculated with the following formula; r/Y*100 [12]

Part III

Acceptable angulation of forearm fractures

Chapter 6

Systematic review on the functional outcome after treatment of a traumatic bowing fracture of the lower arm in children

Linde Musters
Joost W. Colaris

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ABSTRACT

Introduction Traumatic bowing is a commonly missed diagnosis on which only little information is available, inadequate treatment can cause permanent function loss.

Method A systematic review would determine what the effect is of treatment of traumatic bowing of the lower arm in children on the functional outcome. A search on Embase, Medline, Web of Science, Scopus, Cochrane, PubMed publisher, CINAHL and Google scholar, last accessed at the 15th of May 2016. Intervention of interest was treatment; with reduction, reduction and cast or cast only. The primary outcome measure was (I) function; pro and supination, (II) posttraumatic function, (III) posttreatment function and (IV) residual bowing.

Results Five articles were included. Treatment by reduction only showed a normal function, 4 weeks to 8 weeks of cast and reduction followed by cast, both resulted in 0 degrees to 20 degrees residual of pronation loss.

Discussion The treatment was overall well tolerated, had a direct effect and lead to faster restore of function. It is unclear to what amount of bowing can be accepted without any loss of function. But in view of the few complications and good results for reduction, the overall opinion is to reduce all significant bowing fractures of the lower arm in children with limited function.

Level of evidence: IIa

Keywords: Trauma; Pediatric; Lower arm; Bowing; Plastic deformity

INTRODUCTION

Traumatic bowing of the forearm was described first in 1974 [1]. Traumatic bowing is a commonly missed diagnosis on which only little information is available. However, has long lasting consequences when missed. [1, 2].

The main reason for this diagnosis to be missed is that there is no fracture line visible on the conventional radiology. Furthermore, this type of fracture does not follow the standard radiographic phases of fracture healing [3]. The available information is based on small series of patients with no long term follow up [2].

The typical trauma mechanism is a fall on an outstretched hand. Patients present with pain, deformity and function loss. The first weeks no evident radiological abnormalities are found, but after five to six weeks some periosteal thickening on the concavity of the bowing can be seen. There is no standardized protocol for bowing fractures of the lower arm in children. There is some consensus in literature about the group under four years and over ten years of age, however, a consensus in the current literature is lacking in the group between four and ten years with the highest prevalence [2].

The etiology is well known due to *in vitro* and *in vivo* animal research on canine ulnar bones. Bone has a certain elasticity which allows it to bend and restore('elastic deformity'). However, when the bone is bend over the maximal elasticity (150% bodyweight), hundreds of micro fractures appear, which lead to irreparable damage with a remaining bowing ('plastic deformity') (Figure 1/2). This bowing can be seen on a conventional x-ray, when made in correct anteroposterior/ lateral direction of the wrist and the elbow [1, 4].

Currently, the best available measure method for bowing of the radius is the one of Schemitsch an Richards, which has been validated in 2004 by Firl et al. for children (Figure 3).

They discuss two different values; *x/y x 100* and *r/y x 100*. The average maximum value of the radius until the maximal bowing independent of age is 60,39 percent (x/y x 100) and the average bowing independent of age is 7,21 percent(r/y x 100), respectively (Figure 4/5)[5].

METHOD

This review was conducted in accordance with the Cochrane Collaboration guidelines for systematic reviews and meta-analyses; the PRISMA-statement and GRADE quality assessment were used during drafting of the manuscript.

ELIGIBILITY CRITERIA

Study types
The search strategy for this systematic review was limited to randomized controlled (RCT), case-controls and case-series.

Types of patients
Inclusion was limited to studies on patients under eighteen years with an acute traumatic bowing of the lower arm.

Types of intervention
Intervention of interest was treatment with closed reduction or conservative with cast only.

Types of outcome
The primary outcome measure was (I) function, in particular pro and supination of the lower arm. Secondary outcomes were (II) posttraumatic function, (III) post-treatment function and (IV) residual bowing .

Objectives
To compare literature on the effect of treatment and the functional outcome in children with traumatic bowing fracture of the lower arm.

DATA SOURCES

Studies were independently selected by 2 reviewers (L.M. and J.S.) via a systematic search of electronic databases; Embase, Medline, Web of Science, Scopus, Cochrane, PubMed publisher, CINAHL and Google scholar. All were last accessed at the 15th of May 2016 (Table 1). The reference lists of included articles were utilized to maximize search sensitivity. Only published articles were reviewed. Abstracts from meetings, letters to the editor, unpublished reports and review articles were excluded. All languages were considered, if translation was possible.

STUDY SELECTION AND DATA EXTRACTION

Two reviewers (L.M. and J.S.) independently screened all retrieved studies based on title and abstract. This selection yielded 21 articles which met the inclusion criteria, consisting of age <18yr, traumatic bowing of the forearm (ulna, radius or both), treatment existing of conservative, cast or closed reduction and cast.

Exclusion criteria are; age ≥18yr, radial head fracture or dislocation (Monteggia facture), no trauma, ORIF or CRIF.
In case of disagreement, a third party (J.C.) was consulted. Finally, five articles were usable to assimilate (Figure 6).

Risk of bias assessment
Two authors (L.M. and J.S.) independently assessed methodological quality of the included studies. This critical step in the review process evaluates the risk of bias; the risk of bias assessment was performed with use of the Cochrane risk of bias assessment tool. Results are summarized in Table 2 [6].

RESULTS

Included studies
Search on Embase, Medline, Web of Science, Scopus, Cochrane, PubMed publisher, CINAHL and Google scholar provided 2593 articles. After removing duplicates 1280 articles remained. Based on its title and abstract, 21 article abstracts were retrieved in full text and reviewed in duplicate (L.M and J.S.). Sixteen of these articles did not meet the inclusion criteria. The remaining five articles were included in the review, four case series and one prospective cohort study (Figure 6).
Study characteristics are shown in Table 1a and b. Studies were performed in Belgium and America between 1974-2003. A total of sixty patients were included. 24 (40%) female, 28 (47%) male and 8 (13%) with unknown gender. Main age was 8,3 years. Twenty-five (42%) children sustained an isolated ulna bowing, 16 (27%) an isolated radial bowing and 19 (32%) a bowing of both long bones in the lower arm [1,2,3,7,8].

Outcomes measures
Four out of five studies (80%) cover our main outcome measure, pro- and supination after treatment [1,2,7,8]. Half of these studies also describes the direct posttraumatic function in degrees function loss in pro or supination [2,8].
Four out of the five studies (80% describe the type of treatment, variating between closed reduction alone, closed reduction followed by four to eight weeks of immobilization by a cast or only four to eight weeks of immobilization [1,2,7,8].
Furthermore four of the five (80%) studies describe the amount of bowing in degrees posttraumatic and the remaining bowing after treatment.
Three out of five studies (60%) are in favor of reduction to decrees function loss. Borden '75 describes a persisting loss of function after a bowing fracture, when no reduction is attempted. Sanders et al, describes a faster and better function after reduction compared to no reduction

6

cases in the literature. And finally, Vorlat et al. advices reduction at an earlier age >6 years and >10 degrees of bowing/loss of function.

DISCUSSION

No previous systematic overview in literature has been written on traumatic bowing of the lower arm in children to our knowledge. We found that there is a weight of evidence in favor of treatment of traumatic bowing by reduction having a beneficial effect on the outcome.
However, the included studies in this review had several limitations. All populations were small numbers variating between eight and seventeen patients. The type of studies were mostly case reports or case series. Furthermore, the majority of the available articles were not recent and dated.
The amount of bowing in degrees was not documented by Borden '75 and Crowe, and scarcely by the three other studies. Furthermore, the posttraumatic function in degrees of pronation and supination was only documented by Borden '74. Type of treatment was not reported by Crowe, the other studies all describe different types of treatments. The mechanism of reduction seems similar, but the duration of immobilization by cast varies. Furthermore, the amount of residual bowing after treatment is incompletely documented, by the majority of the studies. The same accounts for the incomplete documentation of functional outcome, which was listed as "incomplete", but was also documented as "limited" or "100%". The limited function is not split in the amount of pronation and supination loss.
Three studies have extensive follow up variating between two and 157 weeks, Borden '74 and Crowe do not report any follow up. This lack of information renders it difficult to make statements on the effect of residual bowing and functional outcome and on the beneficial effect of the different treatment strategies.
This review was conducted in accordance with the Cochrane Collaboration guidelines for systematic reviews and meta-analyses; the PRISMA-statement and GRADE quality assessment were used during drafting of the manuscript. Nonetheless, only 5 articles were suitable for inclusion with all small sample sizes variating between eight and seventeen patients. A lot of data is lacking, but attempts to uncover these data all failed, due to the long period since the publication of these articles, the authors were all unattainable.
The current incidence of plastic deformity of the lower arm in children is probably higher than currently estimated, because 25 percent of the cases is discovered during treatment for other lesions of the arms [8]. Several reasons for the low detection of this diagnosis are; difficultly of the interpretation of the deformities on standardized x-rays, insufficient knowledge on the possibility of the diagnosis under doctors in the Emergency Room and an ambiguous presentation.
Borden et al. is the first to describe this plastic deformation of the lower arm in children in

the literature [1]. This hypothesis was confirmed by the principle of plastic deformation of long bones in *in vivo* and *in vitro* animal experiments [4]. These studies concluded that the long bones of children have a different force-formation curve (Figure 2) compared to adults. When a force of 100-150 percent of bodyweight is supplied of both ends of the bone, micro fractures appear on the concave side of the bowing, leading to a plastic deformity. Bowing of the bone causes a minimal hemorrhage in the periosteum of the entire diaphysis. This leads to a late radiologic finding of mild cortical broadening on the concave side of the bowing, without any callus, usually 4-6 months after trauma [8] (Figure 1b). There are three types of bowing fractures of the lower arm in children; (i) Bowing of one long bone and a greenstick of the other, (ii) bowing of both long bones, (iii) bowing of the ulna with a radial head fracture or luxation (Monteggia).

It is recommended to measure the bowing using the in 2004 validated measure method of Firl et al [5] (Figure 4). When the bowing exceeds 7,21 percent, a bowing fracture should be considered (Figure 3). Literature shows that 60 cases of bowing have been described, which were included for this review. 25 of these children had an isolated ulna bowing, 16 an isolated radial bowing and 19 bowing of both long bones. All groups are small (max. … cases), and therefore no significant statements can be done concerning; the effect of type of treatment on the primary outcome (*pro or supination loss and residual bowing*).

Four of the five studies (80%) cover our main outcome measure, pro- and supination after treatment [1,2,7,8]. Half of the studies also describes the direct posttraumatic function in degrees of function loss of pro or supination [2,8]. These values variate between 15- and 30-degrees supination loss. Two articles describe limited pro or supination, without specification in degrees [3,7]. Results do show that 25 children (42 percent) had a persisting pronation or supination limitation at follow-up [3,7].

There were three different types of treatment; (i) reduction only, (ii) reduction followed by minimal four to maximal eight weeks of cast or (iii) four to eight weeks cast only. (Table 3)

Treatment by closed reduction showed a normal function at follow-up. When treated with four to eight weeks of cast a residual loss in function is seen variating between zero and 25 degrees of pronation loss. Treatment with reduction followed by cast also shows a remaining function loss between zero and 20 degrees of pronation loss.

Four out of five articles (80% describe the posttraumatic residual bowing in degrees and half of these studies also describe the residual bowing in degrees after treatment.

The average posttraumatic ulnar bowing is 20 degrees, the average posttraumatic radial bowing is fifteen point two degrees. The average residual ulnar bowing after treatment is eight point six degrees, the average residual radial bowing is four point one degrees [Table 4] . All show a clear decrease in bowing after treatment. The treatment was overall well tolerated, had a direct effect and lead to faster restore of function [8].

There is no protocol for treatment of plastic deformity of the lower arm in children, but there is consensus in literature concerning children <four years of age. Literature states that

these children can be treated conservatively with cast, unless bowing exceeds 20 degrees, then reduction is advised. On the main group age four to ten years, no consensus has been reached. In the available literature altering advises are described, variating from conservative treatment, reduction when >20 degrees to reduction only when limited function is present at presentation [8]. The group of children over ten years of age has less remodeling potential, and, therefore the consensus is that all bowings more than ten degrees necessitate reduction for optimal functional outcomes [2]. Furthermore, reduction is always advised when the bowing of one long bone complicates reduction of the other long bone. It is unclear to what amount of solitary bowing can be accepted without any loss of function. But in view of the low risk of complications and good results after reduction, the overall opinion is to reduce all significant bowing fractures of the lower arm in children with limited function [8].
Ideally a randomized controlled trial should be initiated, in which two groups of reduction versus non-reduction are being compared. One group with reduction followed by cast and one group with only cast, corrected for the degrees of bowing and age of the patient. This might aid in the determination of the optimal treatment policy is depending on age and severity of bowing. Unfortunately, this is hard to facilitate, mainly because of the scarce knowledge on the topic by treating physicians and low incidence. Hopefully this review will give prominence to this diagnosis, which will facilitate prospective studies in the future.

CONCLUSION

Traumatic bowing of the lower arm in children is currently underexposed and frequently missed. It is a difficult diagnosis due to scarce knowledge under doctors in the Emergency Room, an ambiguous presentation and late visibility on standardized x-rays. A possible late radiologic finding is a mild cortical broadening on the concave side of the bowing, without any callus, usually four to six months after trauma [8] (Figure 1b). This plastic deformity of the lower arm can give distinctive function loss, by decrease in pro or supination when not treated properly. Treatment consists of reduction under general anesthetics by exerting force with 100-150 percent of the patient's body weight on both ends of the long bone for a few minutes. This leads to a direct radiological result and an improvement of function, by increase in pro or supination. Reduction is well accepted by patients, therefore when the bowing of the radius exceeds seven-point twenty-one percent, reduction should be considered as a treatment option (Figure 3) [5]. Hopefully this article will lead to a better awareness of this diagnosis so adequate treatment will follow and function loss can be prevented.

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6

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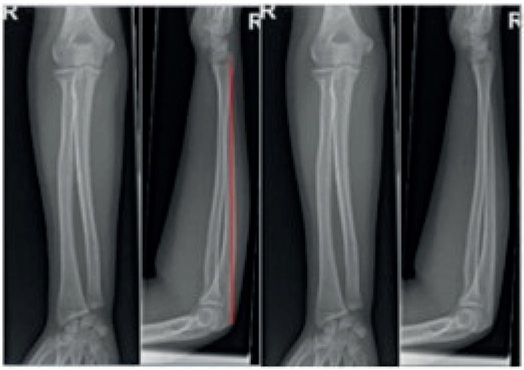

Figure 1 Post traumatic X-ray of the right lower arm with a bowing of the ulna of 5.6 degrees

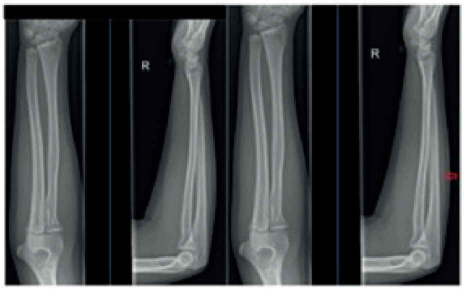

Figure 2 X-ray 6 weeks post traumatic, clear sign of periosteal thickening of the ulna with a bowing of 3.9 degrees

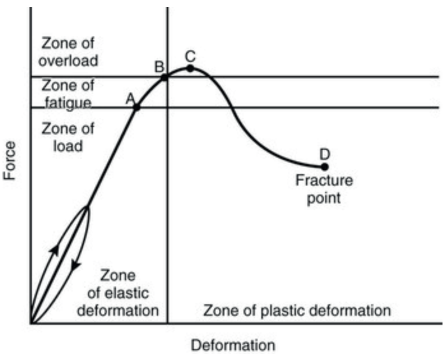

Figure 3 Relation between bowing and effect of force(longitudinal) on the irreparable elastic zone and weakening of the bone in the zone of irreparable damage are shown [1].

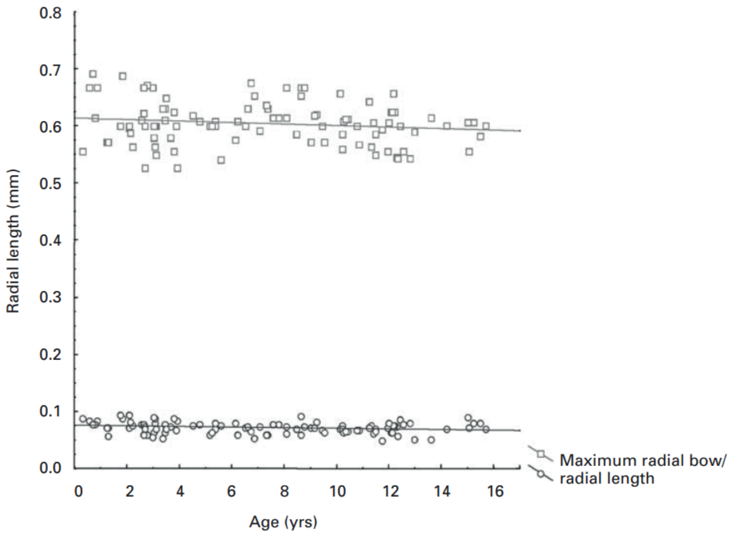

Figure 4 Measure method for bowing of the radius validated in 2004 for children, derivate from the method of Schemitsch and Richards, point of maximal bowing, x/y × 100= 60.39%, maximal radial bowing, r/y × 100- 7.21.

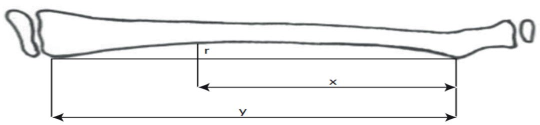

Figure 5 AP X-ray of the radial bone; (y) length of the radius, measured from the biceps tuberosity-radioulnar joint, (x) distance from the biceps tuberosity to the maximal bowing, (r) distance from the maximum point bowing till the y line.

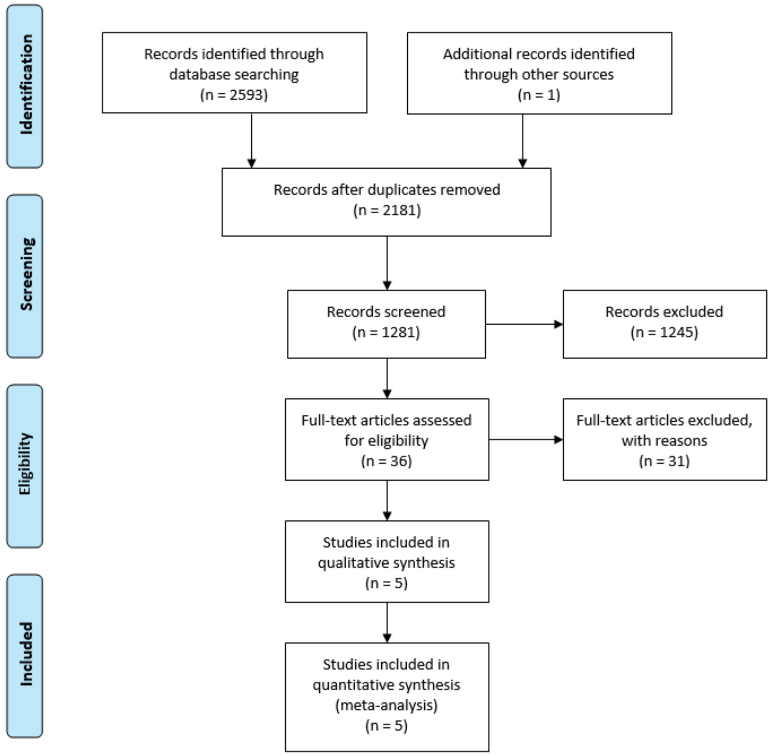

Figure 6 PRISMA 2009 flow diagram

Table 1 Data sources

Embase.com	1040	1022
Medline Ovid	685	83
Web of science	194	46
Scopus	455	42
Cochrane	14	1
PubMed publisher	16	7
CINAHL (EBSCOhost)	61	6
Google scholar	128	73
Total	**2593**	**1280**

Table 2. Risk of bias assessment by Cochrane

Item (+/-/?)	All articles >5 cases
1. Is this study based on a clearly defined group of patients which is determined on the same time in the course of the disease?	bowing of the ulnar/radial bone/both, acute posttraumatic <1 week--> yes +/ no-
2. Is the follow up sufficiently complete?	≤ 5 patients, 80 percent follow up--> yes+/ no-
Outcome(s)	
3. Are the outcomes of the study explicate and objectively disclosed?	function in pro or supination, through DASH or function tool, pain--> yes+/ no-
4. Is the measure of the outcome(s) valid and reliable?	X
5. Ae the outcome(s) independently (blindly) set?	amount of degrees with goniometer--> yes+/ no-
Prognostic	X
6. Are the prognostic factors explicitly and objectively disclosed?	
7. Is follow up available of an enough proportionate group of the included patients?	Long-term follow-up >6 months--> yes+/ no-
8. Is the measure of the prognostic factors of all patients implemented the same way?	amount of degrees according to measure method of Schemitsch & Richards-->yes+/ no-
9. Is the measure of the prognostic factors valid and reliable?	reference to article of Schemitsch & Richards--> yes+/ no-
10. Is the measure of the prognostic factors available of an enough proportionate group of the included patients?	X

Table 3. Overview of data of the included articles

Author	Year	Country	Type	Amount	Polulation			Outcome						
					Sex	Age (yr/months)	Bone bowed	Type	# degrees of bowing	Function posttraumatic	Treatment	# degrees bowing after treatment	FU(weeks)	Function
Borden	1974	USA	Case series	8	F	2,4	Ulna	degrees, P/S	7	30 degrees sup loss	cast 3 weeks	7	65	100%
					M	8,8	Both		R20/ U13	?	reduction + cast 3 weeks	R5/ U0	3	100%
					M	11,4	Both		R17/ U14	15 degreees sup loss	reduction	R0/ U4	12	100%
					4F/1M	6,4-13,8	3R/ 2U		?	limited	reduction	?	no	limited
Borden	1975	USA	Case series	17	9F/8M	2,0-11,5	3R/ 4U/ 3both	degrees, P/S	?	?	no	?	no	?
Crowe	1977	USA	Case series	11	?	3,0-14,0	?	?	?	?	?	?	?	?
Sanders	1983	USA	Prospective cohort	13	7M/6F	4,0-15,0	2R/ 5U/ 6both	degrees, P/S, reduction, x-ray	?	?		3,4	18	
					M	4	both				no		3	?
					M	8	both				reduction		12	?
					F	5	both				no		12	?
					M	5	both		R15/ U15		reduction	R5/ U4	18	?
					M	7	both		R20/ U15		reduction	R6/ U9	12	100%
					M	8	both		U25/ R?		reduction	U18	4	?
					F	10	Radius		10		reduction	0	4	?
					F	10	Radius		16		reduction + cast 6 weeks	0	3	100%
					F	6	Ulna		30		reduction	16	2	?
					M	6	Ulna		35		reduction	15	0	?
					F	8	Ulna				reduction		6	100%
					F	6	Ulna				no		0	?
					M	15	Ulna		22		reduction	11	6	?
Vorlat	2003	Belgium	Case series	11	9M/2F	4-dec	3R/ 6U/ 2both	degrees, P/S, pain		limited pro/ supination			157	

Author	Year	Country	Type	Amount	Polulation				Outcome					
					Sex	Age (yr/months)	Bone bowed	Type	# degrees of bowing	Function posttraumatic	Treatment	# degrees bowing after treatment	FU(weeks)	Function
							Ulna		36	?	reduction + cast 4-8 weeks	10	151	100%
							Ulna		?	?	cast 4-8 weeks	?	49	100%
							Ulna		?	?	cast 4-8 weeks	?	157	limited
							Ulna		13	?	reduction + cast 4-8 weeks	9	26	limited
							Ulna		15	?	reduction + cast 4-8 weeks	0	132	100%
							Ulna		?	?	cast 4-8 weeks	?	109	100%
							Radius		16	?	cast 4-8 weeks	16	85	100%
							Radius		15	?	reduction + cast 4-8 weeks	0	45	100%
							Radius		8	?	reduction + cast 4-8 weeks	5	43	100%
							Both		13	?	cast 4-8 weeks	13	36	100%
							Both		20	?	reduction + cast 4-8 weeks	8	48	100%

Table 4; Calculation of average bowing in degrees

Posttraumatic bowing(in degrees)		Residual bowing after treatment (in degrees)	
ulna	(7+13+14+15+15+25+30+35+22+36+13+15)/12=20	ulna	(7+0+4+4+9+18+16+15+11+10+9+0) /12=8,6
radius	(20+17+15+20+10+16+16+15+8)/9 = 15,2	radius	(5+0+5+6+0+0+16+0+5)/9 = 4,1

Chapter 7

What is the acceptable degree of radiographic angulation for the conservative management of pediatric forearm fractures?

Linde Musters
Kasper Roth
Ruurd Jaarsma
Joris Ploegmakers
Max Reijman
Denise Eygendaal
Joost Colaris

Submitted

ABSTRACT

Background There are still some dilemmas regarding treating forearm fractures of the growing paediatric skeleton. Our study aims to provide an overview of acceptable radiographic angulation based on a systematic review of the literature combined with an expert opinion.

Methods A systematic search was conducted to identify eligible studies on acceptable angulation for conservative treatment of common paediatric forearm fractures; distal radius fractures with and without the involvement of the physis, distal metaphyseal and diaphyseal both-bone fractures, bowing fractures, and radial neck fractures. Additionally, expert opinions on acceptable angulation were collected via an online questionnaire.

Results Our literature search resulted in 2827 articles of which 185 were included in this review. 48 expert opinions were analysed. Results of both literature search and expert opinion were presented in Isala graphs.

Conclusion The degree of acceptable angulation varies based on fracture location and decreases with age. This review suggests that, for most common types of paediatric forearm fractures, a higher degree of angulation could be accepted than what is recommended by current guidelines and what is typically practiced in clinical settings. We advise amending the guidelines and adjusting clinical practice accordingly. The provided tables and Isala graphs offer valuable support in the decision-making process regarding accepting angular deformities in paediatric forearm fractures.

Level of evidence

Level 2b

INTRODUCTION

Forearm fractures are the most common fractures in children, representing 40 to 50 percent (%) of all paediatric fractures (1)(2). The growing skeleton of a child has a remodeling capacity and can correct deformity in time, especially in younger children with residual growth. Fractures located close to the more active growth plate as the distal radius growth plate tend to have more remodeling capacity (3).

In a recent study of 258 children presenting at the emergency department with distal radius fractures, 55% of all children underwent closed reduction with procedural sedation and analgesia (PSA), of which 27% were considered potentially unnecessary (4). This leads to unnecessary risks due to PSA (5), additional treatment time, discomfort, and an unnecessary burden on the healthcare system. Additional operative stabilization results in 15% complications when using k-wires and 16% complications when using intra-medullary nails (6,7).

On the other hand, a persisting malunion of a radial fracture may result in chronic pain and loss of range of motion and occurs in around 5% of the cases (8). Although angulated paediatric forearm fractures are famous for their tendency for spontaneous correction by remodeling, they are still considered unpredictable by many (3). The systematic review by Ploegmakers et al., published in 2006, suggested acceptable angulations for most common forearm fractures in children (3) The aim of this review is to provide an up-to-date review of literature, compared to the current clinical opinion, and to be able to make an evidence-based comment on the current guideline.

Materials and methods

This review is reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (9). It was registered at PROSPERO under the number CRD42018107596.

ELIGIBILITY CRITERIA

Study type

The search strategy for this systematic review was limited to randomised controlled trials (RCTs), case controls and case series, both prospective and retrospective.

Only published articles were reviewed. Abstracts from meetings, letters to the editor, and unpublished reports were excluded. All languages were considered if translation was possible into English.

Types of patients
Inclusion criteria were age <17 years, and fracture of the forearm (ulna, radius, or both), regardless of treatment type.

Exclusion criteria were; age ≥17 years, open fractures, Monteggia and Galeazzi fracture-dislocations and radial head fractures.

Patients were subdivided according to the following fracture types: distal radial fractures involving the physis, distal radius fractures, distal metaphyseal both-bone fractures, bowing fractures (which are plastic deformities of the forearm), midshaft diaphyseal both-bone fractures and radial neck fractures. Patients were subdivided into the following age groups: 1-4, 5-9, 10-12 and 13-16 years.

Types of intervention
The treatment being studied was either a cast, with or without a closed reduction, or surgery, which could potentially be followed by a cast.

Types of outcomes
The primary outcome measure was the maximum accepted angulation of a fracture in the sagittal plane on the lateral radiograph that can be treated with no intervention besides possibly applying a cast. We only looked at the angulation in the sagittal plane, for this is the most common deformity used in clinical practice decision making.

In this review, acceptable angulation refers to the radiographic angulation in the sagittal plane of the bone. This might result in a persisting radiological malunion of the bone with or without a visual clinical deformity of the arm. In this review "acceptable" specifically refers to the amount of angulation on the radiograph that is suitable for conservative treatment, with no need for reduction or operation.
Articles reported either a single cut-off value or a range, in which case we used to median of this value for this analysis. All included articles assessed angulation in the sagittal plane, which can only be determined through radiographic imaging. However, the specific imaging modality used—whether MRI, CT, or plain X-ray—was not always clearly specified. For the purposes of this study, the differences in imaging modality are not expected to significantly impact the results.

Objectives
The first objective was an up-to-date review of literature on acceptable radiographic sagittal angulation of the forearm, suitable for conservative treatment of most common paediatric forearm fractures.

The second objective was to assess the opinion of international experts on acceptable angulation for conservative treatment of paediatric forearm fractures to compare today's practice to evidence-based medicine.

The third objective was to compare our data with the current guidelines to suggest possible amendments.

Data sources

Systematic review

For the systematic review, two independent biomedical information specialists performed a search by systematically searching electronic databases: Embase, Medline ALL, Web of Science Core Collection, Scopus, Cochrane Central Register of Controlled Trials, NICAHL EBSCOhost and Google Scholar. They were last assessed on August 6, 2023.

Expert opinion

The expert opinion was gathered by sending an online questionnaire to different orthopedic associations to distribute amongst their members. We gathered opinions from national and international paediatric trauma specialists through the Orthopedic Trauma Association (OTA) and the American Academy of Orthopaedic Surgeons (AAOS), the Dutch Orthopedic Society (NOV), and their subdivision Paediatric Orthopedics (WKO). This online questionnaire asked the respondent to state the maximum acceptable radiographic sagittal and coronal angulation, rotation and translation(in degrees) for 8 common paediatric forearm fractures.

Study selection and data extraction

Two reviewers (L.M. and K.R.) independently screened all retrieved studies based on title and abstract. Data on population size, mean age, sex, type of fracture, accepted angulation and type of study were then extracted from full-text articles.

Most studies specified the age groups for which they determined acceptable angulation. In some cases, a single value was provided for all children under the age of 16. When this occurred, the same cut-off was applied across all age groups in our dataset.

Risk of bias assessment

Two authors (L.M. and K.R.) independently assessed the risk of bias in the included studies. Risk of bias assessment was performed using the Cochrane Risk of Bias tool for randomised controlled trials and the MINORS validation instrument for the non-randomised controlled trials (6).

Statistical analysis
All statistical analyses were performed using Excel 2021 and IBM SPSS Statistics version 28 (IBM Corp, Armonk, NY, USA).

For the systematic review dataset all values were incorporated into a SPSS dataset, where there extrapolated into acceptable angulation per age group. Means were than calculated with standard deviations (SD) per age group and per fracture type.

For the expert opinion, data were collected through the online questionnaire and again a mean with SD was calculated per age group and per fracture type.

FUNDING

The authors did not receive financial support from any organization for this study.

RESULTS

Results for the first objective; an up-to-date review of the literature.
The final search provided 2827 articles, 1986 after removing duplicates. A total of 166 articles were included based on the full-text review, with an additional 19 articles identified through cross-referencing (Table 1)resulting in 185 articles being included in this systematic review (Figure 1).

A total of 18,850 patients were included, derived from 185 articles.; with a mean age of 9.5 (SD 2.3) years and 62% were boys. Thirteen studies focused on distal radial physeal fractures, 50 studies on distal radial metaphyseal fractures, 8 studies on bowing, 65 on distal metaphyseal both-bone forearm fractures, 65 on diaphyseal both-bone forearm fractures and 49 on radial neck fractures (Table 2).

Results for the second objective; to assess the opinion of international experts.
We gathered 48 responses from American and Dutch surgeons, including 40 orthopedic surgeons, 6 trauma surgeons, and 2 paediatric surgeons. Respondents' expertise levels were as followed; 37 consultants, 5 fellows, and 7 registrars. Of the 48, 31 worked at a regional hospital and 17 worked at a University hospital.
In Table 3 and Figure 2, we provided all data and Isala graphs regarding the degree of maximum accepted radiographic angulation in the sagittal plane per type of fracture from our analysis of the literature (in red) and the expert opinion (in blue).

Results for the third objective; to compare our data with the current guidelines.
These results are summarized in the discussion.

DISCUSSION

The ongoing challenge of determining the maximum acceptable radiographic angulation in the sagittal plane for paediatric forearm fractures is significant, as clinicians often struggle to predict the degree of correction that will occur with growth in a paediatric skeleton. Key is the number of years of growth remaining, from the time of injury to physeal closure. On top of that is the difference between boys and girls at what age the physis closes. Sometimes a formal check of the biological bone age from a wrist or elbow radiograph is required, rather than relying on chronological age (168).

In our study the variance in acceptable angulation for each age group addresses the variance in expected years of growth remaining. We are aware of the fact that girls remain two years ahead of boys in maturation, particularly 10 years and older (3).

A painful malunion with impaired function in daily life is clinicians' biggest fear. Although growth often behaves like a friend, remodeling of a malaligned fracture takes time and the pressure on cosmetic appearance makes it even harder to convince parents to continue conservative treatment for a visibly crooked arm, even with the promise of remodeling (4). This article will guide clinicians in treating paediatric forearm fractures in the least invasive way possible with the best clinical outcome.

There are no recent systematic reviews on maximum accepted radiographic angulation in common paediatric forearm fractures. The most recent comprehensive systematic review was published by Ploegmakers et al. in 2006 (3). Since then, there has been a notable surge in published articles, suggesting the presence of updated information on this subject matter. This overview resulted in updated statements on maximum accepted radiographic angulation based on the literature, and it also integrates current insights from clinical experts worldwide. In general, the literature tends to be more forgiving than current clinical practice, which might be caused by the urge to operate without substantiated evidence (169). This article can hopefully support the decision-making process of acceptance of angular deformities in paediatric forearm fractures.

Fractures involving the radial physis
Regarding the distal radial physeal fractures, current literature states that more complications

occur when there is over 20% angulation or >50% translation (170). The most frequently encountered complications are post-traumatic damage to the physis with subsequent growth derangement and rotational deficits.

Some premature fusions happen in fractures around the physis (171). Therefore, all distal physeal forearm fractures should be followed up to detect early premature physeal closure because early treatment might be beneficial. Luckily, most children develop no long-term functional deficit due to the high remodeling potential. Our literature analysis suggested that 20° of angulation can be accepted regardless of age. Our experts are more conservative and suggest that in children aged ≥10 years, only 10 degrees of angulation should be allowed.

Following literature, we recommend amendment of current guidelines to accepting 20° of angulation regardless of age.

Distal radius fractures

Traditionally, it has been stated that angular deformity of the distal forearm usually corrects fully with growth of the bone within 5 years (172). In children <10 years large displacement during fracture consolidation did not influence the 10-year functional outcome (173). Therefore, in 2005 Wilkins and O´Brien advised that dorsal angulations up to even 30-35° will remodel satisfactorily in children who have at least five growing years left (174). However, over the years the guidelines have become stricter. In 2008, Hove et al. proposed the treatment guideline that in children below the age of 9, 20° of dorsal angulation should be accepted, 10-15° in children aged 9-13 years, and 5-10° in children aged 13-15 years(175). Our literature analysis showed a mean degree of tolerable angulation of 16-23 degrees, which decreases with age. Likewise, our expert opinion suggested to accept less, allowing only 9-19 degrees. Recent studies demonstrate that even when these fractures result in a malunion, this paediatric population has great remodeling potential with good-to-excellent functional outcomes (176,177). In conclusion, our data suggest a slight amendment of the current guideline accepting more angulation in children ≥10 years. (178–180).

We are currently awaiting the results of the comparison of intervention and conservative treatment for angulated fractures of the distal forearm in children (AFIC). In this ongoing study, children younger than 11 years of age with up to 30° angulation in a distal radius fracture, are randomised between no reduction with cast versus closed reduction (+/- K-wires) and cast (181).

Metaphyseal both-bone forearm fractures

Metaphyseal both-bone forearm fractures are known for their risk of secondary displacement in a cast (182). Our literature indicates that for children under 10 years of age, angulation of

13-21 degrees can be accepted, while for those ≥10 years of age, 9-18 degrees is acceptable. Equal values are maintained by the clinicians. However, guidelines are stricter, recommending angulation of only 10-15 degrees. Looking at the current data and comparing this with the clinical opinion suggests that current guidelines might be overly strict for these fractures, given their remarkable remodeling potential. Therefore, an amendment of the guideline is suggested, accepting more angulation in children <10 years of age (183).

Bowing fractures

Bowing or plastic deformation of the forearm is often overlooked. According to the latest literature review, any bowing greater than 20 degrees accompanied by functional impairment should be corrected due to poor remodeling capacity (155). Both literature reviews and clinicians suggest accepting around 15-20 degrees for children <10 years of age and 10-15 degrees for those ≥10 years of age (178–180). There is no good current guideline on this type of fracture, so we suggest adding "acceptable angulation around 15-20 degrees for children <10 years of age and 10-15 degrees for those ≥10 years of age" to the guideline with the notification to have a low threshold for reduction in case of pro- and supination impairment.

Diaphyseal both-bone forearm fractures

Diaphyseally located both-bone forearm fractures have less remodeling capacity (183). Price et al. studied the long-term outcomes of 39 children with malunions after severe diaphyseal both-bone forearm fractures. Complete remodeling was only seen in 12 out of 39 patients, almost all <10 years of age (184). The residual angulation seen after a diaphyseal both-bone forearm fracture was correlated with functional impairment (185). Our literature analysis shows maximum accepted radiographic angulation ranges from 12-17 degrees for these fractures decreasing with age. Our expert opinion said to allow less angulation for diaphyseal forearm fractures in children of all age groups compared to the literature.

Current literature confirms the current guidelines for midshaft both-bone forearm fractures; 10° of angulation is acceptable in children ≥10 years of age, and <15 degrees in children <10 years of age (186). Therefore, no amendment of current guidelines is needed.

Radial neck fractures:

For radial neck fractures, the current guidelines of the AAOS and Dutch Trauma Association (178–180), only accept 30 degrees of angulation independent of age. Our review of literature states that in children <10 years of age, 26-37 degrees is acceptable, but in children ≥10 years of age, 19-30 degrees is advised. Clinicians handle lower cut-offs of 12-25 degrees than the current guidelines. We recommend implementing an age-specific guideline, suggesting a threshold of 30 degrees for children under 10 years old and 25 degrees for those ≥10 years of age.

Limitations and strengths

Limitation of this study are little data on some fracture types, only 13 articles on distal radial fractures around the physis and 8 for bowing. Literature is still scarce and therefore some suggested maximum accepted radiographic angulations are based on little data. However, this is the best evidence available.

We incorporated 19 additional articles through cross-referencing. Considering this represents a significant portion of the total 150 articles, we conducted a reverse search to ensure these articles weren't overlooked in our initial search. However, it was found that all these articles were indeed included in our initial search but were excluded based on abstract or title. This suggests a potential need for more abstracts and titles to describe these articles' content more accurately.

Another limitation of this review is that we did not differ for sex. Key is the number of years of growth remaining, from the time of injury to physeal closure. The mean age for closure of the physis differs between boys and girls: 14.5 and 12.9 years, respectively (187). It is sometimes wise to formally check the biological bone age from a radiograph of the wrist or elbow than to rely on chronological age (168). Most articles, unfortunately, did not distinguish between the sex of the patients. Therefore, we had to decide not to include a sub-analysis based on sex in this systematic review.

Another limitation of our study was the restricted selection of expert associations for gathering opinions. Distributing our questionnaire proved challenging, as engaging with members of prominent associations required membership, which is often unattainable without practicing in the relevant country. Despite these obstacles, we successfully obtained expert opinions through the Orthopedic Trauma Association (OTA), the American Academy of Orthopaedic Surgeons (AAOS), the Dutch Orthopedic Society (NOV), and its subdivision, Paediatric Orthopedics (WKO).

The final limitation is that we haven't been able to include coronal angulation translation and rotation. Despite diligent attempts to extract relevant data from the literature, a significant portion was missing, rendering it impossible to draw conclusive statements. However, sagittal angulation, primarily resulting from a Fall On an Outstretched Hand (FOOSH), is the prevailing post-traumatic deformity in paediatric forearm fractures. Assessment of rotational malalignment via standard X-rays is challenging, leading to its non-standard calculation in this context. The correction of rotational malalignment by remodeling is controversial and considered very limited (188).

The strength of this study lies in its integration of data from current literature with updated clinical expert opinions on the same issue. This approach makes the conclusions highly practical and readily applicable in daily practice.

CONCLUSION

The conclusion of this systematic review of literature is that 14-24 degrees of sagittal deformity is acceptable for all distal radial fractures involving the physis, 12-27 degrees is acceptable for distal radius fractures, 9-21 degrees is acceptable for metaphyseal both-bone fractures, 9-21 degrees is acceptable for bowing, 9-21 degrees is acceptable for diaphyseal both-bone forearm fractures, and 19-37 degrees for radial neck fractures.

This review highlights a general trend suggesting that, for patients under 10 years of age, a higher tolerance for fracture angulation is often accepted for conservative treatment compared to what current guidelines recommend. Conversely, for patients aged 10 years and older, less maximum accepted radiographic angulation is typically advised than what is outlined in existing guidelines. Our expert opinion indicates that daily practice remains cautious, adhering to the lower cut-off values. We recommend that guidelines and clinical practice be updated accordingly.

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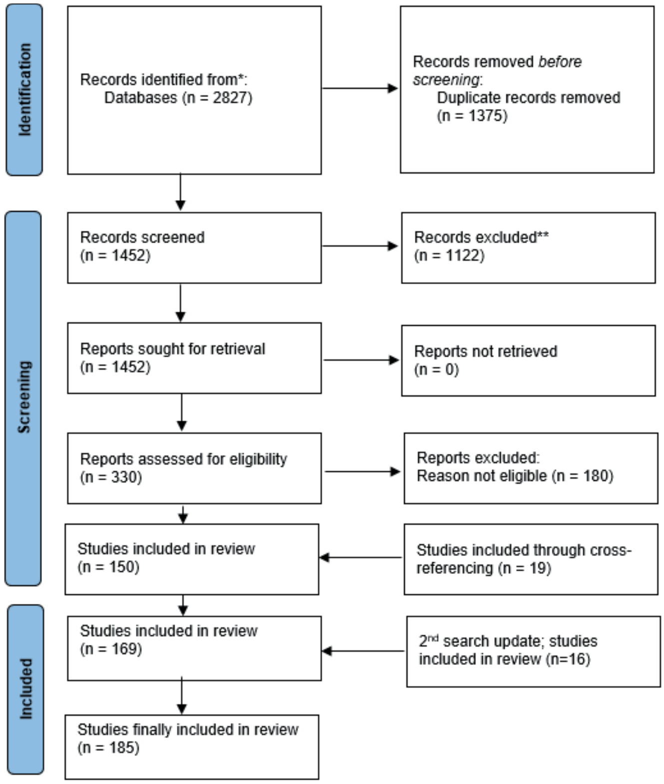

*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).

**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

Figure 1. Prisma Flow-diagram

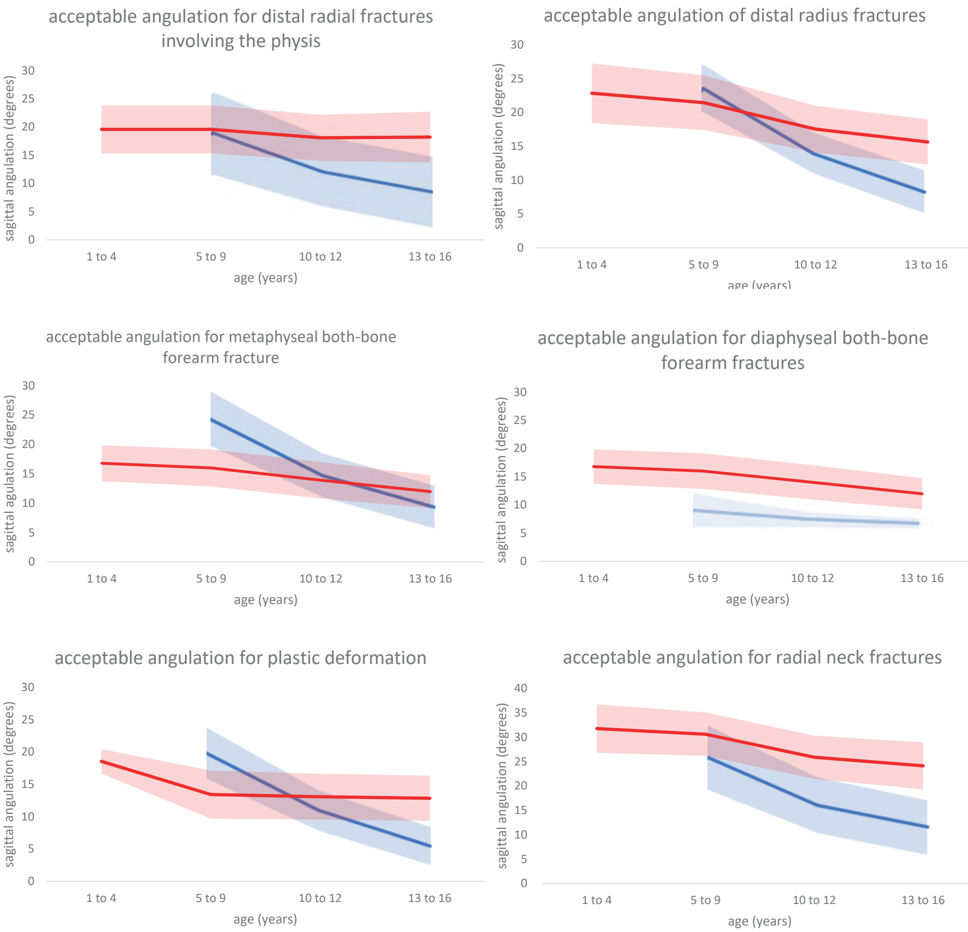

Figure 2. Acceptable sagittal angulation per type of forearm fracture.
Blue=expert opinion update, mean (SD), red= literature update, mean (SD) X=age (years), y= acceptable sagittal angulation (degrees)

7

Table 1. Data sources

	# 1st search	# after the removal of duplicates	# 2nd search
Embase.com	911	894	397
Medline Ovid	988	340	1290
Web of science	523	127	205
Cochrane CENTRAL	36	1	13
CINAHL EBSCOhost	169	5	26
Google scholar	200	85	55
Total	2827	1452	1986

Table 2. Number of articles per fracture type

Type of fracture	Number of studies included
distal radial fractures involving the physis	13
distal radius fractures	50
metaphyseal both-bone fractures	65
bowing fractures	8
diaphyseal both-bone fractures	65
radial neck fractures	49

Table 3. Maximum radiographic acceptable angulation in the sagittal plane of common types of paediatric forearm fracture per age group, *degrees(SD)*

Type of fracture	Age (years)	Expert opinion	Literature and our advice
distal radial fractures involving the physis	1-4	-	20°(15-24)
	5-9	19°(12-26)	20°(15-24)
	10-12	12°(6-19)	18°(14-23)
	13-16	9°(2-15)	18°(14-23)
distal radius fractures	1-4	-	23°(19-27)
	5-9	24°(21-28)	22°(17-26)
	10-12	15°(11-18)	18°(14-21)
	13-16	9°(5-12)	16°(12-19)
metaphyseal both-bone fractures	1-4	-	17°(14-21)
	5-9	24°(19-29)	16°(13-20)
	10-12	15°(11-18)	14°(11-18)
	13-16	9°(6-13)	12°(9-15)
bowing fractures	1-4	-	19°(17-21)
	5-9	20°(16-24)	13°(10-17)
	10-12	11°(8-14)	13°(10-17)
	13-16	6°(3-9)	13°(9-16)
diaphyseal both-bone fractures	1-4	-	17°(14-21)
	5-9	8°(5-11)	16°(13-20)
	10-12	6°(5-7)	14°(11-18)
	13-16	5°(4-6)	12°(9-15)
radial neck fractures	1-4	-	32°(27-37)
	5-9	25°(19-32)	31°(26-35)
	10-12	16°(10-21)	26°(22-30)
	13-16	12°(6-17)	24°(19-29)

Part IV

Factors affecting the functional outcome of the forearm

Chapter 8

Which factors are associated with a long-term functional impairment after a pediatric both-bone forearm fracture?

Kasper Roth
Linde Musters
Leon Diederix
Pim Edomskis
Denise Eygendaal
Joost Colaris

Submitted

ABSTRACT:

Introduction:

Some fracture displacement can be safely accepted in pediatric forearm fractures due to their remodeling capacity. No studies have yet determined which factors are associated with inferior long-term outcomes after pediatric forearm fractures. This study assessed the minimum four-year outcomes of children with diaphyseal or metaphyseal both-bone forearm fractures. Our research questions were: (1) Which factors are associated with a long-term functional impairment after a pediatric both-bone forearm fracture? (2) Do accepted re-displacements lead to inferior long-term outcomes after forearm fractures?

Materials and Methods:

This retrospective cohort study included pediatric patients with metaphyseal or diaphyseal both-bone forearm fractures with a minimum four-year follow-up. Our primary outcome was a long-term functional impairment, defined as a limitation in pro-supination of ≥15° compared to contralateral or a QuickDASH score of ≥20 points. Multivariate logistic regression analysis was performed to identify factors associated with long-term functional impairment. Furthermore, functional and radiographic outcomes were compared between patients with accepted re-displacements and good alignments.

Results:

In total, 316 participants with 149 diaphyseal and 167 metaphyseal fractures were included, with a mean follow-up of 7.2 years. Predictors for limitation in pro-supination of ≥15° at long-term follow-up were: complete initial displacement of the radius, re-fracture, diaphyseal fracture, and bicortical ulnar fracture. A predictor for a QuickDASH score ≥20 points was a bicortical ulnar fracture. There were no clinically relevant differences at long-term follow-up between patients with accepted re-displacements versus those with good alignments.

Conclusions:

Factors associated with long-term functional impairment after both bone forearm fractures include complete initial displacement of the radius, re-fracture, diaphyseal fracture, and bicortical ulnar fracture. Accepted re-displacements did not lead to inferior long-term outcomes. These factors should be taken into consideration to tailor treatment strategies for pediatric forearm fractures.

Level of Evidence: Level II.

INTRODUCTION

Although forearm fractures account for 38% of pediatric fractures, long-term follow-up studies are scarce, which hampers the determination of the best treatment strategy. [28; 30; 38]. Treatment of forearm fractures in children varies from cast immobilization to closed reduction with or without additional stabilization [7; 8]. Re-displacement occurs in up to 51% of displaced metaphyseal and 46% of diaphyseal both-bone forearm fractures [4; 33]. Due to remodeling by growth, a forearm fracture with some displacement can be safely accepted in the expectance that remodeling will occur [38]. Angular deformity of the distal forearm usually entirely remodels within two to five years, provided the epiphysis does not fuse [17; 26]. On the contrary, in midshaft forearm fractures, growth will not correct the angular deformity as it does in distal fractures [19]. The final loss of forearm rotation is correlated with the residual angulation of the radius seen after a diaphyseal forearm fracture [39]. There is a trend toward more operative management, although no long-term outcomes studies have shown superior results following an operation [14]. Franklin et al. stated that high-level evidence for decision-making regarding pediatric forearm fractures is extremely limited [16]. They recommended a long-term follow-up study, with pro-supination as the primary outcome, to aid in evidence-based decision-making for treating pediatric forearm fractures.

Previously, we reported the short-term outcomes of 410 children with diaphyseal or metaphyseal both-bone forearm fractures to assess "*Which factors affect limitation of pronation/supination after forearm fractures in children?*" [9]. In this series, re-displacements occurred frequently and were accepted to consolidate in a malunited position in approximately half of the cases, as remodeling by growth was expected. The assessment of the long-term follow-up of this cohort is essential to evaluate and potentially adjust the treatment strategy for pediatric forearm fractures. Therefore, this retrospective study aimed to investigate the clinical outcomes after both bone forearm fractures in these children, using prospectively gathered data with a minimum follow-up of four years. Our research questions were: (1) Which factors are associated with a long-term functional impairment after a pediatric both-bone forearm fracture? (2) Do accepted re-displacements lead to inferior long-term outcomes after metaphyseal and diaphyseal forearm fractures?

PATIENTS AND METHODS

Study design, setting, and participants

Between 2006 and 2010, 410 children with both-bone forearm fractures were included, and their short-term outcomes were reported with a mean follow-up of 7 months [9]. Currently, we report the long-term follow-up of this cohort, with a minimum follow-up of four years. The following inclusion criteria were used: children aged <16 years at trauma with a diaphyseal or metaphyseal both-bone forearm fracture in the diaphysis or distal metaphysis. Metaphyseal forearm fractures are located in the distal third, whereas diaphyseal forearm fractures are defined as fractures in the shaft between the distal and proximal metaphysis. Exclusion criteria were open fractures.

Description of Treatment:

Closed reduction of a pediatric both-bone forearm fracture was performed in case of ≥50% displacement, ≥15° of angulation in children aged <10 years, and ≥10° of angulation in children aged 10-16 years. Re-displacement was defined as the re-occurrence of a displacement meeting the initial reduction criteria during cast treatment. The protocol stated to perform a re-manipulation for all re-displacements. An accepted re-displacement was defined as a re-displacement that met the abovementioned criteria for reduction but was left untreated to consolidate in a malunited position. Other alignments were considered good alignments. The included children were participants in several randomized controlled trials (RCTs) in which treatment protocol was based on the fracture location, need for reduction, and stability [5; 7; 8; 10; 11]. Metaphyseal fractures without the need for reduction were randomized to a below-elbow cast (BEC) or an above-elbow cast (AEC) for four weeks [10]. Fractures meeting the reduction criteria underwent a closed reduction in the operating room under general anesthesia. After closed reduction, a stress test was performed in all patients to assess fracture stability. A fracture was defined as unstable if performing maximum pronation or supination caused re-displacement under fluoroscopy [8; 25]. Stable reduced metaphyseal fractures were randomized to treatment with or without K-wires fixation and received an AEC for four weeks [7]. Unstable reduced metaphyseal fractures were treated with K-wires fixation. Diaphyseal fractures without reduction or stable after reduction were treated with AEC for six weeks or early conversion to a BEC after three weeks [8; 11]. Unstable diaphyseal fractures were treated with one or two intramedullary nails [5].

Variable, Outcomes measures, Data Sources, and Bias

Our primary outcome measure was a long-term functional impairment, defined as a limitation of ≥15° of pro-supination or a QuickDASH score of ≥20 points at long-term follow-up. Measuring pro-supination was standardized using a 180° goniometer constructed of clear, flexible plastic with two movable arms of 30 cm. The smallest detectable difference (SDD) for measuring pro-supination in children after forearm fractures by conventional goniometry was 15° in our previous study [6]. Sardelli et al. stated that up to 65° of pronation and 77° of supination may be required during specific contemporary tasks [32]. The minimal clinically important difference (MCID) for the shortened version of the Disabilities of the Arm, Shoulder, and Hand questionnaire (QuickDASH) was determined at 20 points [15]. We analyzed the following factors: age at trauma, fracture location, fracture type (greenstick vs. bicortical), the complete initial displacement of radius or ulna, and (untreated) re-displacement and re-fracture by performing uni- and multivariate logistic regression. Next, we compared outcomes between patients with accepted re-displacements and good alignments at consolidation to investigate if accepted re-displacements lead to inferior (functional, radiographic, and patient-reported) outcomes at long-term follow-up. We subdivided between diaphyseal and metaphyseal re-displacements. One orthopedic registrar examined patients at short-term follow-up. Another orthopedic surgeon examined patients at long-term follow-up. Angulation was defined as the total degree of deviation of the distal fragment in relation to the proximal fragment. The intramedullary angulations were measured according to a standardized technique [4].

Statistical methods

To rule out selection bias, patients lost to follow-up were analyzed by comparing the included patients' demographics with those lost to follow-up (in Table 1). For categorical variables, the Chi-square test was used. For continuous variables, the independent samples t-test was used. Next, univariate logistic regression analysis was performed to identify factors associated with a functional impairment at long-term follow-up. A p-value of <0.10 was used as a threshold to determine which factors progressed to the multivariate logistic regression analysis. Outcomes between patients with accepted re-displacements and good alignments were compared using the independent samples t-test.

Ethics, data sharing, funding, and potential conflicts of interest

Our institutional review board approved this study, registered under protocol number NL41839.098.12. All authors declare no conflict of interest. No funding was received.

RESULTS:

Participants, descriptive data

Between 2014 and 2016, 316 out of 410 participants (77%) were included, with a mean follow-up of 7.2 years (range 4.2 to 10.3). There were 149 diaphyseal fractures (46%) and 167 distal fractures (54%). The mean age at trauma was 8.1 years (range 0.9 to 16.5). There were no significant differences between the included patients and those lost to follow-up (Table 1).

Fracture characteristics, re-displacements, and re-fractures

In Figure 1, we present an inclusion flowchart. Of the metaphyseal fractures, 66 out of 212 (31%) were minimally displaced. 146 out of 212 (69%) were displaced and underwent closed reduction, of which 128 (92%) were deemed stable and randomized between K-wire fixation versus casting, whereas 18 (8%) were unstable and received K-wires. In patients treated without stabilization, re-displacements occurred in 30 out of 67 (45%) reduced metaphyseal fractures, whereas 15 out of 66 (23%) of non/minimally displaced metaphyseal fractures were re-displaced in cast. Re-displacements were accepted in 31 out of 50 (62%) patients. Regarding the diaphyseal fractures, 47 out of 198 (24%) were minimally displaced. 151 out of 198 (76%) were displaced and treated by closed reduction. 127 out of 151 (84%) were deemed stable, whereas 24 out of 151 (16%) were unstable and were treated with intramedullary nails. In patients without stabilization, re-displacements occurred in 44 out of 127 (35%) reduced diaphyseal fractures and 12 out of 47 (26%) non/minimally displaced diaphyseal fractures. Re-displacements were accepted in 39 out of 56 (70%). Re-fractures occurred in 24 out of 149 diaphyseal fractures (16%) and 18 out of 167 metaphyseal fractures (11%). A bicortical ulnar fracture was frequently accompanied by a bicortical radius fracture (86%).

In the metaphyseal group, minor complications (excluding re-displacement) occurred in 22 out of 78 patients who received K-wire fixation (28%), whereas in 6 out of 127 (4.7%) patients who did not receive K-wire fixation. In the diaphyseal group, minor complications (excluding re-displacement) occurred in 9 out of 24 (38%) patients treated by intramedullary nailing, whereas in 20 out of 174 (11%) patients treated without intramedullary nails. The minor complications after K-wiring or intramedullary nailing consisted of transient neuropraxia of the superficial radial nerve, subcutaneous K-wires requiring operative removal, wound dehiscence, and superficial infections that did not require additional surgical intervention.

Long-term functional impairment

A limitation of ≥15° pro-supination occurred in 16% of patients at minimum four-year follow-up: 12% in the metaphyseal group and 20% in the diaphyseal group ($p = 0.06$). A QuickDASH score of ≥20 points occurred in 7% of patients.

Results of uni- and multivariate analysis for factors associated with a functional impairment at long-term follow-up are presented in Tables 2 and 3, respectively. Predictors for limitation in pro-supination of ≥15° at long-term follow-up were complete initial displacement of the radius, re-fracture, diaphyseal fracture location, and bicortical ulnar fracture. A predictor for a QuickDASH score ≥20 points was a bicortical ulnar fracture. Age at trauma was not associated with long-term functional impairment.

Accepted re-displacements

Accepted re-displacement of a metaphyseal forearm fracture led to no differences in long-term radiographic outcomes (Table 4A). Accepted re-displacement of a diaphyseal forearm fracture led to a statistically significant difference in persisting sagittal angulation of the radius (5.6° vs. 3.8°). At long-term follow-up, there were no significant differences in functional outcomes (ABILHAND, QuickDASH, cosmetic scores or hand grip strength) between patients with accepted re-displacements versus good alignments (Table 4B).

DISCUSSION

This study investigated the following questions: (1) Which factors are associated with a long-term functional impairment after a pediatric both-bone forearm fracture? (2) Do accepted re-displacements lead to inferior long-term outcomes after metaphyseal and diaphyseal forearm fractures?

Factors associated with a functional impairment

Predictors for a functional impairment at a minimum four-year follow-up were: a complete initial displacement of the radius, diaphyseal fracture location, bicortical ulnar fracture, and a re-fracture. In our study, a limitation of ≥15° pro-supination occurred in 16% of patients at minimum four-year follow-up: 12% in the metaphyseal group and 20% in the diaphyseal group. Although this difference was not statistically significant during the independent samples t-test (p=0.06), multi-variate logistic regression analysis did reveal that a diaphyseal fracture location was statistically significantly associated with persisting impairment in pro-supination. Previously, two cadaveric studies demonstrated that angular deformities of the forearm bones can cause an important loss of pro-supination, especially in middle-third deformities [24; 34]. Furthermore, diaphyseal angular deformities are less likely to remodel because the nearer the fracture to the physis, the greater the potential for spontaneous correction [17]. Hence, diaphyseal fractures were more likely to cause a persisting pro-supination limitation at minimum four-year follow-up than metaphyseal fractures, in our study. Re-fractures lead to a new injury of the healing interosseus membrane and twice the length of cast immobilization, which increases the probability of impaired pro-supination. In line with previous results, we also found that re-fractures occur more often after diaphyseal than after distal forearm fractures [3]. In our study, bicortical ulnar fractures were frequently accompanied by bicortical radius fractures, which makes this a group of high-energy trauma and related soft tissue damage.

Metaphyseal forearm fractures

Zamzam et al. stated that predictors for re-displacement of metaphyseal fractures were complete initial displacement of the radius (odds ratio of 25) and a both-bone fracture (odds ratio of 23) [37]. Nevertheless, if complete remodeling occurs, a re-displacement will not lead to long-term functional impairment. In our study, patients with accepted re-displacements after metaphyseal forearm fractures did not have inferior long-term outcomes compared to those with good alignments, which illustrates the exceptional potential for remodeling. In a previous study, re-manipulation of re-angulated distal forearm fractures in children did not improve outcomes at four-year follow-up compared to patients with accepted re-angulations [31]. Furthermore, Zimmermann et al. studied 232 pediatric distal forearm fractures and found that large displacements (>20° angulation) in children aged <10 years did not influence the long-term outcomes [38]. Crawford et al. accepted distal radius fractures with 100% dorsal translation in 51 children aged <10 years and witnessed excellent outcomes in all children [12]. Literature showed remarkable potential for remodeling in pediatric forearm fractures, still, there is a natural tendency to try to make each fracture radiographically more anatomic [13]. In pediatric distal radius fractures, remodeling speeds of 2.4° of angulation per month have been observed [20; 23]. Orland et al. stated that 27% of closed reductions performed in children <10 years are potentially unnecessary [27]. Improved awareness of these acceptable deformities in young children may reduce the number of children requiring reduction with sedation [27]. Van Delft et al. reported the following commonly-used criteria for acceptable alignment of distal forearm fractures: 30° dorsal and 15-20° radial angulation in children aged ≤9 years and 20° of dorsal and 10° radial angulation in children aged >9 years [35]. We await the results of the AFIC and CRAFFT trials with great anticipation, in which children aged <11 years with severely displaced distal radius fractures are randomized between cast immobilization with or without closed reduction [1; 2].

Diaphyseal forearm fractures

Regarding diaphyseal forearm fractures, Yang et al. stated that risk factors for re-displacement were a bicortical fracture type (odds ratio of 9.6) and a poorer reduction (odds ratio of 8.5) [36].

In our study, accepted re-displacement of a diaphyseal forearm fracture led to significantly more persisting sagittal angulation of the radius (5.6° vs. 3.8°). It is debatable if this difference is clinically relevant. However, a diaphyseal fracture location was also significantly associated with a persisting functional impairment at four-year follow-up.

Gandhi et al. stated that mid-shaft angular deformity corrects poorly, resulting in pro-supination limitation [17]. Price et al. studied the outcomes of 39 children with malunions after severe diaphyseal both-bone forearm fractures with a mean follow-up of 6 years. Complete remodeling occurred in only 12 out of 39 patients, of which 11 were <10 years at trauma [29]. In a study by Zionts et al. residual angulations of <10° after closed reduction for diaphyseal forearm fractures led to excellent outcomes in 75% of cases, whereas residual angulations >15° provided excellent outcomes in only 40% [39]. In 2006, Ploegmakers et al. published a meta-analysis regarding the limits of acceptance for angular deformation of pediatric forearm fractures. Their study revealed that the tolerable degree of angulation decreases with increasing age. Thus, a two-year-old child should be treated differently than a nine-year-old. Also, girls remain two years ahead of boys in maturation which should influence the treatment strategy [28]. Kay et al. stated that midshaft both bone forearm fractures in children >10 years result in functional deficit more often than is appreciated [22]. Jones et al. recommended performing closed reduction for midshaft forearm fractures in children aged ≤8 years with >10° of angulation and children >9 years with >8° of angulation [21]. We await the results of the first RCT comparing reduction with casting or flexible intramedullary nailing in displaced forearm shaft fractures in children aged 7-12 years [18].

LIMITATIONS

Our key limitation is that the reduction criteria did not differentiate for fracture location (diaphyseal of metaphyseal) or gender, and there were only two age groups (<10 or ≥10 years). Due to the difference in remodeling potential between diaphyseal and distal metaphyseal forearm fractures, our reduction criteria were too strict for distal metaphyseal fractures. A second limitation is that one orthopedic surgeon measured the range of motion.

CONCLUSIONS

Predictors for a functional impairment at long-term follow-up after a pediatric forearm fracture are a complete initial displacement of the radius, diaphyseal fracture location, bicortical ulnar fracture, and re-fracture. Consider that tremendous remodeling can be seen in metaphyseal forearm fractures in children with remaining growth potential. These factors should be taken into consideration during decision-making for patient-tailored treatment of pediatric forearm fractures.

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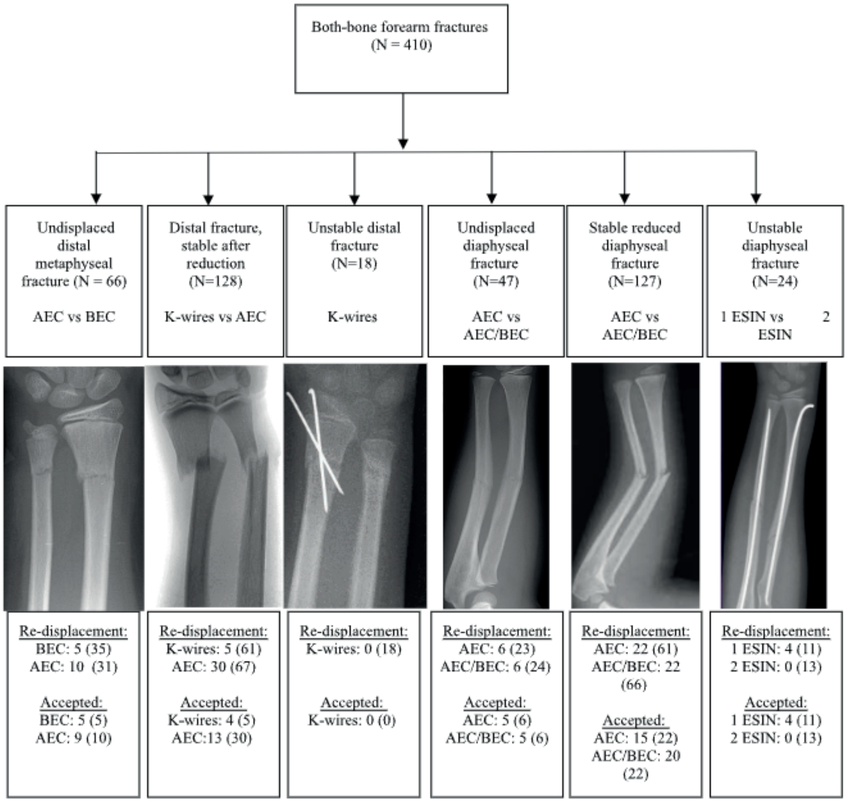

Figure 1. Inclusion Flowchart

Table 1. Representation of Follow-Up Population

	Included for long-term FU (N = 316)	Lost to FU (N = 94)	Mean difference (95% CI)	P-value
Age at trauma	8.0 (±3.3)	8.4 (±3.6)	-0.4 (-1.2 to 0.4)	0.29
Male sex	60% (191)	70% (66)	-9.8% (-21 to 1)	0.09
Bicortical Radius Fracture	53% (167)	56% (53)	-3.2% (-15 to 9)	0.59
Bicortical Ulnar Fracture	39% (122)	40% (37)	-1.0% (-13 to 10)	0.86
Re-Displacement rate	27% (84)	27% (26)	0.0% (-10 to 10)	0.99
Accepted Re-Displacements	19% (59)	21% (11)	-2.6% (-12 to 7)	0.57
Loss in Pro-Supination at 6m FU	11.6° (±13.8)	13.9° (±15.1)	-2.3° (-6 to 1)	0.17
Complications	27% (86)	29% (27)	-1.2% (-12 to 9)	0.82

Data presented as % (n) or mean ±SD , unless noted otherwise

Table 2. Uni-Variatie Logistic Regression

	Dependents			
	≥15° limitation in pro-supination at long-term FU		≥20 points QuickDASH at long-term follow-up	
Factors	Exp (B)	P-value	Exp (B)	P-value
Age at Trauma	1,06	0.19	1,12	0.08
Diaphyseal Location Fracture	1,83	0,05	1,28	0.59
Bicortical Radius Fracture	2,41	0.008	2,12	0,14
Bicortical Ulnar Fracture	2,61	0.002	3,10	0.022
Complete Initial Displacement Radius	1,91	0.068	1,48	0.47
Complete Initial Displacement Ulna	2,84	0.067	-	-
Accepted Re-Displacement	1,44	0.32	0,76	0,67
Re-Fracture	2,90	0.005	0,69	0,63

Table 3. Multi-variate Linear regression analysis:

	Models			
	≥15° Loss in pro-sup at long-term FU		QuickDASH ≥20 points at long-term FU	
	Exp (B)	Significance	Exp (B)	Significance
Complete Initial Displacement Radius	2,8	0.02	-	-
Re-Fracture	2,7	0.01	-	-
Diaphyseal Location	2,3	0.03	-	-
Bicortical Ulna Fracture	2,2	0.02	3,1	0.02

Table 4.A Radiographic long-term outcomes (Accepted re-displacements)

	Accepted re-displacement	Good alignment	Mean difference (95% CI)	P-value
Distal metaphyseal fractures				
Radius - PA	4.9° (±3)	5.0° (±4)	-0.04° (0.8 to -1.6)	0.96
Radius - Lateral	4.2° (±3)	3.7° (±3)	0.4° (-0.9 to 1.8)	0.53
Ulna – PA	5.0° (±3)	4.8° (±3)	0.3° (-1.1 to 1.7)	0.70
Ulna - Lateral	3.1° (±3)	3.5° (±3)	-0.4° (-1.8 to 1.0)	0.58
Diaphyseal fractures				
Radius - PA	9.1° (±3)	9.2° (±3)	-0.1° (-1.3 to 1.1)	0.86
Radius - Lateral	5.6° (±4)	3.8° (±3)	1.8° (0.5 to 3.0)	0.007
Ulna – PA	5.3° (±3)	5.2° (±3)	0.1° (-1.2 to 1.4)	0.88
Ulna - Lateral	4.7° (±3)	4.5° (±3)	0.2° (-0.8 to 1.2)	070

Table 4.B Functional long-term outcomes (Accepted re-displacements)

	Accepted re-displacement	Good alignment	P-value
Distal metaphyseal fractures			
ABILHAND	41.4 (±1.4)	41.6 (±1.4)	0.59
QuickDASH	4.7 (±9)	4.0 (±8)	0.67
NRS cosmetics	8.7 (±1.5)	8.3 (±2.1)	0.20
Jamar ratio	100.5% (±18)	99% (±20)	0.67
Diaphyseal fractures			
ABILHAND	41.8 (±0.5)	40.5 (±5.3)	0.20
QuickDASH	3.7 (±4.8)	5.5 (±10)	0.35
NRS cosmetics	8.0 (±1.8)	8.4 (±2.0)	0.34
Jamar ratio	94.4% (±17)	98.0% (±16)	0.29

Part V

Summary and discussion

Chapter 9

General discussion, clinical implications, and future perspective

Forearm fractures are common in the pediatric population. Despite their large numbers, it is a challenge to enroll young patients with this pathology in clinical studies with an adequate follow-up. However, medium to long-term follow-up studies are essential in order to define evidence-based treatment guidelines. In this thesis, we fortunately had access to the data of a large group of pediatric patients with forearm fractures of previous studies by J.W. Colaris et all (1–4).

In this general discussion, the findings and conclusions of the studies described in this thesis are mirrored to current guidelines, insights, and findings of other studies based on five questions. Additionally, we provide suggestions for future research.

Q1. IS IT WORTHWHILE TO PERFORM LONG-TERM FOLLOW-UP STUDIES ON PEDIATRIC FOREARM FRACTURES?

In the initial section of this thesis, we have outlined the long-term follow-up results of children with metaphyseal and diaphyseal forearm fractures. Long-term follow-up studies in pediatric patient groups are sparse in the literature. There are several explanations for this, firstly, including the perception among medical doctors that pediatric patients possess a high potential for restoration, leading to a lack of perceived necessity for follow-up. Secondly, children and parents may be reluctant to return to the hospital for minimal complaints due to factors such as long travel distances and competing priorities in young families. These factors lead to the lack of available studies and data on the natural course and the long-term follow-up of these injuries. Nevertheless, it is essential to assess the outcome after these fractures to predict which type of fractures in which age group are prone to functional impairment. Given the high life expectancy of children, any changes in functional outcome will have a significant impact on their Quality of Life.

First, children with minimally displaced metaphyseal forearm fractures (Chapter 2) will be addressed. These fractures are relatively forgiving. At seven months follow-up no difference was seen between children treated with an above or a below elbow cast in functional outcomes despite the high rate of secondary displacement (17% in the BEC group vs 32% in the AEC group). All children showed a good restore of function in both groups. There was a preference for below elbow cast due to less discomfort and reduced interference in daily life. This preference was substantiated at the seven-year follow-up, as both groups had similar outcomes, loss of rotation and PROMs. The advice would be to treat these fractures with below elbow cast for 4 weeks.

Secondly, children with reduced metaphyseal forearm fractures will be assessed. This is a slightly more complicated group as they experienced more secondary displacement, leading to more malunions and functional impairment at the seven months follow-up. Consequently, one can understand that long-term follow-up is of greater importance here, allowing for the assessment of remodeling effects on fracture malunion and on functional outcomes. The short-term follow-up study showed less re-displacement when K-wires were added to an above elbow cast (45 vs. 8%), less limitation in rotation (mean 6.9° (±9.4) vs. 14.3° (±13.6) but more complications 14 vs. 1 (4). The minimum five-year follow-up showed significantly more malunions in the AEC group compared to the K-wire group (19 vs. 7%). But there was no significant difference in forearm rotation (loss of prosupination for both groups of around 5 degrees) and PROMs between these groups. Treatment advice would involve performing one attempt in the emergency department under sedation/local anesthetic after obtaining informed consent from the parents. Cases should be pre-selected with a good chance of a successful outcome. If this initial attempt fails, the next step would be to proceed to the theater for a closed reduction with k-wire fixation. Subsequently, apply a below-elbow cast for 4 weeks, depending on the age of the child.

Next diaphyseal both-bone forearm fractures are discussed. This is a group of even more interest, known for its higher rates of malunion and secondary impaired forearm rotation. The underlying mechanism involves a greater distance of the fracture to the growth plates, resulting in less remodeling potential. But also possible bony blocking and soft tissue contractures that can lead to less rotation (5,6).

First, we will assess if the long-term follow-up provides new insights into the treatment and outcomes of the non-reduced group. Although these non-reduced fractures are generally considered stable, Colaris et al. showed a high rate of secondary displacements in cast (43% in the AEC groups vs 4% in the AEC/BEC group). Short-term follow-up showed rotational impairment, with 30 degrees for the AEC group and 23 degrees for the AEC/BEC group. Long-term follow-up demonstrated continuous improvement over time, averaging in only 8-degrees of rotational loss. Importantly, no noticeable limitations were reported by the patients in daily life in both groups. Long-term follow-up of these pediatric populations highlights significant improvement even after seven months, suggesting a potential need for longer clinical follow-up. But also, consideration of a longer wait-and-see period is warranted before proceeding to corrective surgery, because nature appears to be mild in this population group. However, it can be challenging for both children and their parents to endure years of waiting for remodeling to correct the angulated forearm and restore rotation. The treatment suggestion would be for conservative treatment with an AEC for three weeks, followed by three weeks of a BEC.

When looking at the reduced diaphyseal group, indifferent of initial treatment, there is a clear improvement in functional and radiological outcomes over time, with significant improvement in rotation from the 7-month mark to the 7.5-year mark. This group again showed high rates of malunions. Twenty-seven percent had a radiological malunion after removal of the cast, of which 65% remodeled at seven months. Interestingly, this study showed that even at 7.5-year follow-up the remaining group of 13 children with persisting malunion has twice as much radial angulation at final follow-up (8.2 vs 4.3 degrees (95% CI of -5.9 to 1.9, p<0.001)). However, the natural course was mild because functionally there was no difference compared to the non-malunion group. Again, this would not have been discerned without a long-term follow-up. Treatment advice for this group would be conservative treatment with three weeks of an above-elbow cast, follow by three weeks of a below-elbow cast.

Clinical implications	
Minimally displaced metaphyseal fractures	Below-elbow cast for 4 weeks
Reduced metaphyseal fractures	One attempt to reduction in ED under sedation/ local anesthetics Failed--> closed reduction + k-wire fixation in theater + below-elbow cast for 4weeks
Non-reduced diaphyseal fractures	3 weeks above-elbow cast, followed by 3 weeks of a below-elbow cast
Reduced diaphyseal fractures	3 weeks above-elbow cast, followed by 3 weeks of a Below-elbow cast
Malunions	<1 year, give remodeling a chance to improve both functional and radiological outcome >1 year consider corrective osteotomy

Q2. DOES THE ACCEPTABLE ANGULATION FROM THIS THESIS EQUAL THE ADVISED ACCEPTABLE ANGULATION FROM THE CURRENT GUIDELINE?

Guidelines summarize the current medical knowledge based on updated recent literature, they weigh the benefits and harms of diagnostic procedures and treatments, and give specific recommendations based on this information (7). Although guidelines are seen as important tools that support decision-making there is still a lack of adherence to guidelines worldwide (8). Nonetheless, doctors are ethically obliged to adhere to guidelines, as they must base their actions on up-to-date scientific information and employ recognized treatments appropriately. When they choose to deviate from guidelines, they are expected to provide an explanation for their decision.

To gain a clear overview of the current 'state of art' treatment advice for pediatric forearm fracture, several guidelines and treatment rationales have been assessed and compared, including the Royal Australian College of General Practitioners (RACGP),), Dutch Society for Trauma Surgery (NVT) the Australian Orthopedic Association (AOA) and websites Royal Children's Hospital Melbourne, AO Surgery and Orth bullets (9–13). One remarkable finding is that most current guidelines are based on dated literature, which aligns with expectations due to the high costs and considerable effort required for adjustments. Moreover, classification of different fracture types lacks, and broad nonspecific interpretations are sometimes given.

For instance, the Australian RACGP guideline is based on only 3 articles, whilst the Dutch guideline is based on multiple studies. The website of the Royal Children's Hospital Melbourne, offers a good and clear overview of all types of fractures and their acceptable angulation and consist treatment suggestions. But their treatment recommendation is based on old studies. The AO Surgery website states that earlier recommendations on acceptable angulation based on x-rays are hard to judge in clinic, and they advise to act on obvious malalignment. This advice is open to interpretation, but most importantly based on expert opinions. Thereby, the Orth bullet website has the best overview of acceptable angulation, but good literature references are lacking as this website is based on expert opinions.

This thesis presents an up-to-date review of literature for acceptable angulation in the most common pediatric forearm fractures, including; distal radial physis, buckle, greenstick, distal radius, bowing (plastic deformation) (Chapter 6), both-bone metaphyseal, both-bone diaphyseal and radial neck fractures (Chapter 7). It is essential to implement these findings as soon as possible in current guidelines to make our 'current state of art treatment' as evidence based as possible. We will further focus on three well known guidelines or treatment rationales on pediatric fracture angulation, and if these are compared to the finding of our systematic review, a number of remarkable findings are seen (see Table 1).

Starting with distal radial physeal fractures, only the AOA guideline gives an advice on these, which is much stricter than the current literature, namely 10-15 degrees, depending age, opposed to 18-20 degrees in literature. Current clinicians are somewhere in the middle with 9-19 degrees, bases on our international questionnaire under experts. Bases on this thesis acceptable angulation of distal radial physeal fractures is <20 degrees for age <10 and <18 degrees for ≥10 years of age.

There is not much advice in the guidelines for buckle fractures. The AOA is the only one that states 10-15 degrees of acceptable angulation. The data on this group from our review of literature were not usable, due to the fact literature did not between diaphyseal and metaphyseal. These two groups have different remodeling potential and therefore we cannot use these data. The results from the questionnaire under clinical experts show they agree on roughly 10-25 degrees of angulation in the sagittal plane depending on the age of the child, the younger the child the more can be accepted, which is slightly more than the current guideline. No statements can be made on the need for amendment of the guideline.

For greenstick fractures it is the same, not much advice is given in the current guidelines, only the AOA stated 10-15 degrees of acceptable angulation. Our review on literature again was not usable due to the same reason as mentioned above. Out clinical experts advised 8-23 degrees of angulation, again depending on age. Again, no statements can be made on the need for amendment of the guideline.

An interesting recent study by Spierings et al. showed non-inferiority of direct discharge using a removable splint for simple greenstick/ buckle fracture without any further clinical follow up, compared to current treatment with a backs lab, BEC and removal of plaster in clinic (14).

The next group comprises distal radius fractures, which are the most common type of fracture. All guidelines provide advice on these: less than 15-30 degrees for children under the age of ten and less than 10-20 degrees for children over the age of ten. However, this still leaves considerable room for interpretation. The current literature states less than 23 degrees for age under ten and less than 18 degrees for children age of ≥10. Clinical experts are following the guidelines with 9-24 degrees of acceptable angulation. Data from our literature review and gathered expert opinion favors amendment of the guideline. The suggestions would be to narrow the window of acceptable angulation from less than 25 degrees for the age under ten and less than 15 degrees for the age ten and higher.

Moving more proximal in the arm to the diaphysis. First bowing fractures will be discussed, the first systematic review (chapter 6) was only looking at plastic deformation, and included articles from around 1980's. That conclusion was that bowing of more than 20 degrees independent of the age with a functional rotational impairment needs a reduction. With a notification that children over the age of ten have less remodeling potential, and therefore there should be a lower threshold for treatment in this group. Our second systematic review included more recent articles (chapter 7), which concluded that in children under the age of five around 20 degrees is acceptable. In children above the age of five more than 13 degrees of bowing with functional impairment would be an indication for closed reduction.

When looking at both-bone metaphyseal forearm fractures there is more stated in the guidelines. Overall, it states that children under the age of ten less than 15 degrees of angulation can be accepted, over the age of ten this is less than ten degrees of angulation. Our systematic review shows that slightly more angulation is feasible, namely less than 17 degrees for children under the age of ten and less than 13 degrees for children 10 years and older.

The other important group are the both-bone diaphyseal forearm fractures. Guidelines state exactly the same acceptable angulation as for metaphyseal fractures of 10-15 degrees. Even though these type of fractures are known to have less remodeling potential and potentially more contractures of soft tissue (5,6). Because of this, the general idea is that less angulation can be accepted in midshaft fractures. Current guidelines are based on known literature and the problem is that a lot of articles give an acceptable angulation for both bone forearm fractures, and don't distinguish between diaphyseal or metaphyseal. Resulting in comparable acceptable angulation for metaphyseal and diaphyseal located fractures. With the knowledge on remodeling potential, combined with literature data and expert opinion we are inclined to recommend no amendments should be made to the current guidelines.

Finally, we will discuss radial neck fractures. Current guideline(s) states that less than 30 degrees of angulation for every age is acceptable, compared to less than 32 degrees for children under the age of ten and less than 25 degrees for children above the age of ten in literature. Data from our literature review suggests adding different age groups to the guideline, which would state less than 30 degrees is acceptable for children under the age of ten and less than 25 degrees for children 10 years and older.

Table 1. Comparison between current guidelines and our data on acceptable angulation of pediatric forearm fractures.

	NVT	AAOS	Orth bullets	Our data Expert opinion	Our data Literature
Involving distal radial physis	<50% translation	≤9yr <15° >9yr <10° 100% translation	?	5-9yr 19°(12-26) 10-12yr 12°(6-19) 13-16yr 9°(2-15)	1-4yr 20°(15-24) 5-9yr 20°(15-24) 10-12yr 18°(14-23) 13-16yr 18°(14-23)
distal radius fractures	<5yr <30° <10yr <20° <15yr <10°	≤9yr <15° >9yr <10° 100% translation	<10yr<30°, <1cm bayonette >10yr<20°, no bayonette	5-9yr 24°(21-28) 10-12yr 15°(11-18) 13-16yr 9°(5-12)	1-4yr 23°(19-27) 5-9yr 22°(17-26) 10-12yr 18°(14-21) 13-16yr 16°(12-19)
bowing fractures	<10yr <15° >10yr <10° No sec displacement	≤9yr <15° >9yr <10° 100% translation	?	5-9yr 20°(16-24) 10-12yr 11°(8-14) 13-16yr 6°(3-9)	1-4yr 19°(17-21) 5-9yr 13°(10-17) 10-12yr 13°(10-17) 13-16yr 13°(9-16)
metaphyseal both-bone fractures	<10yr <15° >10yr <10° No sec displacement	≤9yr <15° >9yr <10° 100% translation	<10yr<15°, <1cm bayonette ≥10yr<10°, no bayonette	5-9yr 24°(19-29) 10-12yr 15°(11-18) 13-16yr 9°(6-13)	1-4yr 17°(14-20) 5-9yr 16°(13-19) 10-12yr 14°(11-17) 13-16yr 12°(9-15)
diaphyseal both-bone fractures	<10yr <15° >10yr <10° No sec displacement	≤9yr <15° >9yr <10° 100% translation	<10yr<15°, <1cm bayonette ≥10yr<10°, no bayonette	5-9yr 8°(5-11) 10-12yr 6°(5-7) 13-16yr 5°(4-6)	1-4yr 17°(14-20) 5-9yr 16°(13-19) 10-12yr 14°(11-17) 13-16yr 12°(9-15)
radial neck fractures	<30° <50% translation	≤9yr <15° >9yr <10° 100% translation	<30°,<3mm translation	5-9yr 25°(19-32) 10-12yr 16°(10-21) 13-16yr 12°(6-17)	1-4yr 32°(27-37) 5-9yr 31°(26-35) 10-12yr 26°(22-30) 13-16yr 24°(19-29)

NVT(Dutch Society for Trauma Surgery), AOA (Australian Orthopedic Association)

Q3. COULD WE POTENTIALLY ACCEPT MORE ANGULATION IN PEDIATRIC FOREARM FRACTURES?

Saying all this, being a doctor starts with 'Primum non nocere' or 'do no further harm'. This means doctors are careful in their decision making and will rather be on the safe side of the seesaw. This is probably the main reason why practical implementation of change in treatment guideline takes a long time. But also, in absence of clear guidelines clinicians will fall back on their expert opinion. Even though literature has shown that we can probably accept more angulation than the current guidelines imply, it takes a while before the guidelines are amended, and it will take even longer to implement these new recommendations in daily practice.

The biggest hesitation to be more liberal in accepting angulation, is probably the fear of malunion and possible loss of function. But also, the high demand of society on cosmetic appearance, which makes it harder to convince parents to continue conservative treatment for a visibly crooked arm, even with the promise of remodeling. Possibly the introduction of an application that will guide these patients and their parents during their remodeling process would be an interesting idea.

But to convince the child and parents we should know for certain if we can really trust on full correction by growth with restoration of full function.

Chapter 2 showed that the children with a malunion of minimally displaced metaphyseal forearm fractures had complete remodeling and normal function at the seven-year follow-up.

The reduced metaphyseal group showed no difference between the groups in functional outcome (five degrees of loss of rotation) but more malunions were seen when treated with an above-elbow cast alone, opposed to additional k-wires (19 vs 7%) (chapter 3).

In our other study on minimally displaced diaphyseal forearm fractures malunions were rarely seen. Only two patients had severe malunions with secondary severe loss of rotation, that needed corrective surgery. The remaining children had 8 degrees of remaining loss of rotation at final follow-up independent of initial treatment.

We will conclude with the group, most at risk for malunions, namely the children with displaced diaphyseal forearm fractures. Twenty-two patients had persisting radiological malunions at the seven-month mark. Of those twenty-two, thirteen showed persisting radiological malunions at the seven-year follow-up. This confirms the known lower remodeling potential of diaphyseal located fractures. Despite the malalignment, this group shows equal final functional outcome as the non-malunion group. This finding supports the resilience of the pediatric musculoskeletal system. Important is to notice that the worst cases were excluded from the long-term follow-up because they underwent surgical correction and were excluded from follow-up.

The excellent remodeling capacity of the pediatric forearm is again confirmed by our retrospective cohort study (chapter 9) where we looked at all diaphyseal and metaphyseal fractures together. This study showed no differences in functional or radiological outcome between the accepted re-displacements and the well aligned groups, indifferent of being

metaphyseally of diaphyseally located. The only significant difference found was slightly more persisting radial sagittal angulation in malunited diaphyseal fractures (5.6 vs 3.8 degrees), but with no impact on functional outcome at long-term follow-up.
Important note is that statements on excellent and good functional outcome of the forearm, are based on dated literature. The article mostly referred to, when discussion forearm rotation is Morrey et al. 1981 who stated; 'Most of the activities of daily living that were studied in this project can be accomplished with 100 degrees of elbow flexion (from 30 to 130 degrees) and 100 degrees of forearm rotation (50 degrees of pronation and 50 degrees of supination)'(15). A much more recent study by Sardelli et al 2011 implemented several contemporary tasks, such as moving a computer mouse, typing on a keyboard, picking up a cellular phone and holding it against the ear. They have shown that needed range of motion for current daily life ranged from 20.0° ± 18° of pronation to 104° ± 10° of supination. Which results in a needed arc of motion of 124 degrees (16). In cases of persistent impaired rotation, patients can compensate for pronation easier than for supination, with glenohumeral and scapulothoracic movement (17).
In order to determine how much malunion would be acceptable with good evidence-based data, a clinical trial would be unethical. Possible 4D simulation might be an option, which could present different amounts of malunion and their functional outcome. But right now, we have to base our knowledge on incidental malunions. The information we have so far would suggest we can probably accept more angulation than currently advised. Even patients that had a malunion based on the current cut-off, seem to remodel perfectly, with a good/excellent functional outcome.
To answer our previous question "Could we potentially accept more angulation in pediatric forearm fractures?" is probably "yes" (Table 2). We are working on a prediction model to implement this knowledge into daily practice.

<u>Clinical implications</u>

- Implement wait-and-see up to one year as a possible treatment of radiological malunion with functional impairment
    - <1year, give remodeling a change to improve both functional and radiological outcome
    - >1 year consider correction osteotomy

Proposal for new guideline on acceptable angulation for most common pediatric forearm fractures

Table 2. Acceptable angulation of forearm fractures in the sagittal plane.

Type of fracture	Age < 5	Age < 10	Age < 13	Age ≤16
distal radial fractures involving the physis	20°(15-24)	20°(15-24)	18°(14-23)	18°(14-23)
distal radius fractures	23°(19-27)	22°(17-26)	18°(14-21)	16°(12-19)
metaphyseal both-bone fractures	17°(14-21)	16°(13-20)	14°(11-18)	12°(9-15)
Bowing fracture	19°(17-21)	13° (10-17)	13°(10-17)	13°(9-16)
diaphyseal both-bone fractures	17°(14-21)	16°(13-20)	14°(11-18)	12°(9-15)
radial neck fractures	32°(27-37)	31°(26-35)	26°(22-30)	24°(19-29)

Q4. WHY IS IT THAT WE OBSERVE CASES WITH MINIMAL ANGULATION BUT SIGNIFICANT LOSS OF FUNCTION?

In order to be able to answer this question, we need to go into the intriguing facets of the pediatric musculoskeletal system. First, we need to look into the unique characteristics of pediatric bone. Pediatric bone is characterized by the possibility to bend, their remodeling capacity, growth, rapid healing and less stiffness of the surrounding joints after immobilization. Remodeling itself is an interesting process that facilitates initial angulation to correct by growth. This remodeling mechanism makes pediatric fractures amendable to a non-surgical treatment with a cast, were as in adult bones angulation will not remodel at all, and a surgical intervention is often indicated.

There are two laws of physics responsible for remodeling. Wolff's law mostly applies at the diaphyseal level, where bone is being formed where biomechanically needed and resorbed where it is not needed. Hueter-Volksmann's law is the urge of the growth plate to be perpendicular to the shaft and mainly occurs at the epiphyseal level. The further the fracture site is from the growth plate though, the less influence of Hueter-Volkmann's law, and the remodeling will be mostly relying on Wolff's law. Furthermore, angulation in the sagittal plane is better tolerated than in the coronal plane, and rotational angulation will not remodel at all (18). Even though children have amazing remodeling capacity, Bot et al. showed that functional impairment is mostly associated with pain and fear rather than with objective measurements like DASH, rotation, flexion/extension elbow wrist, radiographic angulation, and grip strength (6).

In cases with severe limitation in forearm rotation and minimal angulation there should be a high suspicion for an underlying structural problem preventing rotation like a contracture of the intraosseous membrane. Or when rotation is absent a synostosis between radius and ulna should be considered. These problems would require surgical intervention within reasonable time.

The role of soft tissue contractures in rotational impairment of the forearm, mainly being the interosseous membrane between radius and ulna, has been frequently mentioned in literature but never firmly proven (19–22). Colaris et al. tried to reveal pathology of the interosseous

contracture in children with pro-supination deficit via MRI, but were unable to confirm it (23). But the fact that less physiotherapy sessions resulted in more children with more than 20 degrees of pro-supination loss, does suggest that soft tissue stiffness influences the functional outcome (24).
Even though children have remarkable bone remodeling capacity, we should remain mindful of potential underlying issues such as coping mechanisms, soft tissue contractures, boney impingement or synostosis, which could impede optimal functional outcomes. Even though children have an amazing remodeling capacity of bone, we should be aware of possible underlying coping issues, soft tissue contractures, or synostosis which could prevent good functional outcome.

Clinical implications

- severe functional deficits should be addressed early with physiotherapy to prevent persisting impairment
- in severe persisting functional deficit, not responding to physiotherapy at the one-year mark, an underlying anatomical problem should be excluded

Q5. WHAT ARE THE RISK FRACTURES THAT DO NEED LONGER FOLLOW-UP AND MORE ATTENTION?

The overall above message is that we can be more liberal in our cut-offs for acceptable angulation, early conversions to below-elbow cast and pause with our operative intervention in malunion cases. But awareness should be raised for the few fractures that do need more attention, and the risk factors that are known to result in a potential worse outcome should be known.
The fracture types that need attention are; bowing fractures, fractures with complete displacement of the radius and a complete ulna fracture. Risk factors for worse outcome are diaphyseal location of the both bone forearm fracture, a re-fracture, severe malunions that have not remodeled after one year, or functional deficit without any improvement after one year.
Bowing fractures remain a fairly unknown variant. A bowing of more than 20 degrees with pro-supination impairment can potentially give persistent functional loss, when not treated properly or missed. Treatment consists of reduction under general anesthetics by exerting force with 100% to 150% of the patient's body weight on both ends of the long bone for a few minutes. This leads to correction of the deformity and an improvement of pro-supination. Reduction is well accepted by patients, therefore when the bowing of the radius exceeds 20 degrees it should be reduced (chapter 6). There are two other types of fracture that need more attentions. Our multi-variate logistic regression analysis (chapter 8) showed association

between a complete initial radial displacement or a complete ulnar fracture and more than 15 degrees of final rotational deficit. These types of fracture need early intervention in the operating room and intensive follow-up.
Furthermore, this analysis showed that cases with a re-fracture or a diaphyseal location of the fracture are at higher risk of persisting functional loss as well. In case of a re-fracture this is probably to blame on the combination of secondary trauma to the bone and its surrounding tissues, leading to potentially more constrictions, but also to the extended immobilization with cast contributing to stiffness. Diaphyseal fracture do worse, due to their longer distance to the growth plate, resulting in less remodeling capacity but due to the bigger distance between ulna and radius prevents soft tissues to expand, leading to rotational deficit, more common a lack of pronation (25).
It would be amazing to implement all this knowledge into artificial intelligence (AI) applications were you enter all the data and an AI algorithm will point out which patient is at risk and needs more attention and follow-up.

Clinical implementation:

Fractures that need attention;

- bowing fractures
- fractures with complete displacement of the radius
- complete ulna fractures

Risks for worse outcome;

- diaphyseal location of the both bone forearm fracture
- re-fractures
- severe malunions that have not remodeled after one year
- functional deficit without any improvement after one year

FUTURE PERSPECTIVES

Current guidelines for pediatric forearm fractures still leave room for interpretation on treatment and acceptable angulations for some common pediatric forearm fractures. When studying the references on which the current guidelines are based, they are either scarce or outdated. A suggestion would be to modify existing topics in the guidelines based on the need for updates, following the customary method of evidence-based guideline development. After the revised guideline receives authorization from the relevant parties, the modules can be published on the guidelines database (26). Hopefully this will occur following increased awareness generated by the publication of the review on acceptable angulation for pediatric forearm fractures.

When evidence-based medicine suggests modifications to the current practical guidelines for managing pediatric forearm fractures, the next crucial step is implementation. Through teaching, raising awareness at orthopedic conferences, and utilizing various media, individual surgeons will hopefully be convinced of the necessity of the proposed modifications. Next level is implementation by groups of surgeons/ and orthopedic networks. When they are convinced the national orthopedic society can consider modification of the current guidelines (27).

And when we even dream bigger, we would suggest one guideline worldwide, fully up-to-date based on evidence-based medicine.

Exploring the notion of being overly cautious in the management of pediatric patients with forearm fractures, one might consider entirely eliminating clinical follow-up for low-risk, uncomplicated pediatric forearm fractures. A recent publication by Arvidsson et al. investigated the use of digital follow-up for elderly patients following a simple distal radius fracture, revealing high levels of appreciation for this approach, even among individuals with limited digital literacy (28). More studies show the potential positive impact of virtual clinics in alleviating the burden on hospital resources (29). To translate this to our pediatric population Spierings et al. just published an article looking at results of eliminating follow-up for greenstick and buckle fractures treated with removable splints. Their findings indicate that direct discharge is non-inferior to traditional treatment in terms of treatment satisfaction among pediatric patients, compared to rigid immobilization and routine follow-up. Furthermore, the results reveal no complications, comparable functional outcomes, and a statistically significant reduction in secondary healthcare utilization (14).

The acceptable angulation of forearm fractures, as defined by clinical experts, is often lower than what recent literature suggests. There are several possible issues that need to be addressed. First it is important to create awareness under clinicians, the updated guidelines need to be promoted. Another issue is the pressure placed by modern society on appearance. The cosmetic aspect of the forearm is becoming increasingly important, not only for the child but also for the parents. In order to convince parents of the possibility of treating forearm fractures non-operatively and accept angulation so it can remodel, guidance is essential. We are considering developing an application that will assist patients and their parents during the remodeling process. The guidance could include a timeframe with images of forearms at different stages of remodeling (both x-rays and clinical pictures), as well as advice on exercises and red flags indicating when to return to the hospital. Hopefully, this initiative will contribute to increased acceptance in the long run.

Finally, we are in the process of designing an application or prediction model that incorporates all the data from our systematic review on acceptable angulation in common pediatric forearm fractures. This tool should provide our (young) colleagues in the emergency department with guidance on which angulation can be accepted and which requires intervention of some kind. Furthermore, modern 4D growth, correction and kinematic prediction models could be implemented in application for clinical use as well.

Clinical Implications:

Update of the current guideline advised based on current evidence-based medicine;

distal radial physis	*yes*
distal radius fractures	*yes*
bowing fractures	*yes*
metaphyseal both-bone fractures	*no*
diaphyseal both-bone fractures	*no*
radial neck fractures	*yes*

Conclusion and recommendations

This thesis provides a distinctive insight into the behavior of the pediatric skeleton concerning forearm fractures through long-term follow-up prospective studies. Children with remaining growth showcase excellent remodeling of angular deformities, with a few exceptions that warrant early intervention.

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Chapter 10

Summary

Chapter 1. General introduction

Almost half of the pediatric fractures are forearm fractures. These fractures are located around the distal radial physis in fourteen percent, in the distal metaphysis in 65%, in the diaphysis in 20%, and in the proximal metaphysis in one percent of the cases. The majority of these fractures are treated non-surgically with a cast. However, treating fractures with casts has a notable drawback, as the re-displacement of fractures occurs in 7-39% of cases, potentially leading to malunion. Malunion does not always result in functional impairment as children have an excellent remodeling potency. The ability to remodel depends on two crucial factors; the distance of the fracture to the physis, and the resting growth capacity which is related to the child's age and sex. Insufficient remodeling can result in impaired functional outcomes.

This thesis aims to present unique insights into the behavior of the pediatric skeleton concerning forearm fractures because of its long-term follow-up prospective studies. The objective of this thesis is to supply medical professionals with comprehensive knowledge/evidence-based guidelines regarding the optimal timing, duration, and type of treatment of pediatric forearm fractures. Furthermore, it aims to elucidate the various factors that should be taken into consideration when making treatment decisions.

Chapter 2. Below-elbow cast sufficient for the treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children: long-term results of a randomized controlled multicenter trial

Moving on to specific fracture types, this chapter presents a seven-year long-term follow-up of a randomized controlled trial (RCT) involving children with minimally displaced metaphyseal both-bone forearm fractures. One group received treatment with an above-elbow cast, while the other was immobilized in a below-elbow cast. The latter group reported increased comfort, reduced interference in daily activities, and similar functional outcomes at the seven-month follow-up. This study assesses outcomes at the seven-year follow-up, focusing on the loss of forearm rotation and additional measures, including the loss of flexion-extension of the elbow and wrist compared to the contralateral forearm. Other parameters examined include the QuickDASH score, ABILHAND-kids questionnaire, grip strength (measured using a JAMAR Dynamometer) presented as a ratio of the affected forearm to the contralateral side, and radiological assessment of the angulation of the radius and ulna.

The mean length of follow-up was 7.3 years . Of the initial 66 children who were included in the RCT, 51 children were evaluated at long-term FU, 26 out of 31 patients who were allocated to AEC, and 25 out of 35 patients who were allocated to BEC. Loss of forearm rotation and secondary outcomes were similar in the two treatment groups. Therefore, our recommendation is that children with minimally displaced metaphyseal both-bone forearm fractures should be treated with a below-elbow cast.

Chapter 3. Do We Need to Stabilize All Reduced Metaphyseal Both-Bone Forearm Fractures in Children with K-wires?

This chapter covers patients with a metaphyseal fracture requiring reduction. We present findings from a long-term follow-up RCT involving children randomized into either an above-elbow cast (casting group) or fixation with K-wires and an above elbow-cast (K-wire group). The mean follow-up duration was 6.8 years, with 54 participants in the casting group and 51 in the K-wire group. The patients had a mean age of nine years at the time of trauma and a mean angulation of the radius and ulna of 25° and 23°. Redisplacements were more frequent in cases treated with an above-elbow cast alone (19% vs 7%). Notably, no significant differences were observed in forearm rotation, patient-reported outcome measures, or radiographic parameters between patients treated solely with an above-elbow cast and those receiving additional K-wire fixation. This suggests that re-manipulation and fixation with K-wires should be considered primarily when a child is taken to theater or in case of secondary displacement, taking into account factors such as gender, age, and the direction of angulation.

Chapter 4. Improved forearm rotation even after early conversion to below-elbow cast for non-reduced diaphyseal both-bones forearm fractures in children: a secondary 7.5-year follow up of a randomized trial

This chapter provides an in-depth analysis of the next significant group, children with diaphyseal forearm fractures where no reduction is required. It presents a long-term follow-up of an RCT wherein children were randomly assigned to either an above-elbow cast (AEC) alone or early conversion to a below-elbow cast (BEC). The mean length of follow-up was 7.3 years, with 38 out of the initial 47 children participating. Rotation improved in both groups over time, with no significant difference in the final forearm rotation: 8 degrees for the AEC group and 8 degrees for the BEC group with a mean difference of zero. Furthermore, no difference was seen in PROMs and radiological angulation. We concluded that forearm rotation after a non-reduced diaphyseal both-bone forearm fracture showed a significant improvement after 7.3 years compared to at the 7-months mark, irrespective of the initial treatment. Children aged below the age of nine are likely to experience almost full recovery of function indifferent their malunion. Children above the age of nine did show some cases with severe malunion, but almost all malunions remodeled without any functional loss, emphasizing that the remaining growth behaves as a friend in the long-term.

Chapter 5. Does early conversion to below-elbow casting for pediatric diaphyseal both bones forearm fractures adversely affect patient-reported outcomes and range of motion?

Following the discussion of non-reduced cases in Chapter 4, we now turn our attention to the group with diaphyseal both-bone forearm fractures that do require reduction. The key question addressed is whether early conversion to a below-elbow cast (BEC) should be the recommended treatment, and whether an accepted re-displacement leads to inferior clinical outcomes in the long-term follow-up. The outcomes assessed align with those in our previous studies, with a mean follow-up duration of seven-point-five years and we included of 97 out of 128 participants, 47 in the AEC group and 50 in the AEC/BEC group. Loss of forearm rotation was 8 degrees for the AEC group and 4 for the AEC/BEC group, with a mean difference of 3.8 degrees (p=0.47). The long-term follow-up showed significant improvement in forearm rotation in both groups compared to the rotation at seven months. For the AEC group from 27 at two months to 18 at seven months to 8 degrees at seven years follow-up. For the AEC/BEC group from 22 at two months to 12 at seven months to 4 degrees at seven years follow-up. And, no significant differences were found between groups in terms of primary and secondary outcomes. Thirteen patients with persisting malunion at seven months follow-up showed no clinically relevant differences in functional outcomes at long-term follow-up compared to children without malunion. The loss of forearm rotation was 5.5 for the malunion group compared to 6 in the non-malunion group, with a mean difference of 0.4 (p=0.92). In conclusion, early conversion emerges as the preferred treatment, and the ongoing growth contributes to enhancing function over time, irrespective of the initial treatment, even in cases where the fracture secondarily displaces.

Chapter 6. Systematic review on the functional outcome after treatment of a traumatic bowing fracture of the lower arm in children

This chapter will be addressing a less common pediatric fracture known as the bowing fracture of the forearm. Frequently overlooked, this fracture type has the potential to be missed and may result in impaired forearm rotation. Our systematic review showed that reduction was generally well-tolerated, exerted a direct positive effect, and contributed to a more rapid restoration of function.

The acceptable degree of bowing without incurring any loss of function remains unclear. However, given the minimal complications observed and the positive outcomes associated with reduction, the prevailing consensus is to consider reducing all significant bowing fractures of the forearm in children who present with rotational impairment.

Chapter 7. What is the acceptable degree of radiographic angulation for the conservative management of pediatric forearm fractures?

The upcoming chapter comprises a systematic review focusing on the acceptable angulation of the most common pediatric forearm fractures. The pediatric skeleton, characterized by its unique features, allows for a broader acceptance of angulation than in adults. We reviewed and included 185 articles in our analysis. Included fracture locations are, around the distal radial physis, the distal metaphysis, and the diaphysis. The different fracture patterns included are; bowing, buckle, greenstick, and complete fracture. This review indicates a general trend wherein, for patients under 10 years of age, a higher tolerance for fracture angulation can be

accepted than in the current guidelines. In contrast, for patients aged 10 years and above, less acceptable angulation is typically advised than in the current guidelines. Literature concludes that 14-24 degrees is acceptable for all distal radial fractures involving the physis, 12-27 degrees is acceptable for distal radius fractures, 9-21 degrees is acceptable for metaphyseal both-bone fractures, 9-21 degrees is acceptable for bowing, 9-21 degrees is acceptable for diaphyseal both-bone forearm fractures, and 19-37 degrees for radial neck fractures.
Compared to current guidelines, our combined review and expert opinion suggest that more angulations could be accepted for most common types of pediatric forearm fractures than what is advised in the current guidelines and being accepted in current clinical practice. The advice is to amend guidelines and clinical practice accordingly.

Chapter 8 Which factors are associated with a long-term functional impairment after a pediatric both-bone forearm fracture?
This final chapter addresses two fundamental questions: firstly, the factors associated with pro-supination limitation at long-term follow-up, and secondly, whether accepted re-displacements result in inferior long-term functional and radiographic outcomes. The study focuses on patients with metaphyseal or diaphyseal both-bone forearm fractures, encompassing a minimum of four-year follow-up. Primarily, patients were included in various RCTs, such as those randomized between below-elbow and above-elbow cast (BEC/AEC) for undisplaced distal fractures, closed reduction with or without K-wires fixation for displaced distal fractures, AEC and early conversion to BEC for stable diaphyseal fractures, and one or two intramedullary nails for unstable diaphyseal fractures. Our primary outcome measure was long-term functional impairment (limitation in pro-supination and QuickDASH). Other analyzed factors are age at trauma, fracture location, fracture type (greenstick vs. bicortical), complete initial displacement of radius or ulna, re-displacement, (untreated) re-displacement and re-fracture. The study included 316 out of 410 participants (77%), with a mean follow-up of 7.2 years. There were 149 diaphyseal fractures (46%) and 167 distal fractures (54%). The mean age at trauma was 8.1 years. Analysis showed that predictors for limitation in pro-supination of ≥15° at long-term follow-up were: complete initial displacement of the radius, re-fracture, diaphyseal fracture, and bicortical ulnar fracture. A predictor for a QuickDASH score ≥20 points was a bicortical ulnar fracture. There were no clinically relevant differences at long-term follow-up between patients with accepted malunions versus those with good alignments.
Treatment considerations for metaphyseal forearm fractures are; tremendous remodeling can be seen in children aged under ten years, therefore if re-displacement occurs, the surgeon should discuss accepting re-displacement or performing a re-manipulation (± K-wire fixation), based on the expected remodeling potential. Treatment considerations for diaphyseal forearm fractures are; because one third of stable fractures after closed reduction re-displaces in cast and these fractures show less remodeling potential, additional intramedullary stabilization should be performed with low threshold in children over ten years of age.

Chapter 9. General discussion, clinical implications, and future perspective
This chapter presents the general discussion. In this chapter the most important findings of the thesis are summarized as clinical implications, and future perspectives are discussed.

Conclusion and recommendations
This thesis showed a unique insight into the behavior of the pediatric skeleton concerning forearm fractures because of its long-term follow-up prospective studies. Children with remaining growth exhibit excellent remodeling of angular deformities.
Except for bowing fractures where the prevailing consensus is to consider reducing all significant bowing fractures of the forearm in children who present with rotational impairment and treat them with a short-term cast afterward.
For minimally displaced metaphyseal both-bone forearm fractures the treatment should be a below-elbow cast. When initially displaced, re-displacements were more frequent in cases treated with an above-elbow cast alone, suggesting that especially in children above ten years of age with less remodeling capacity, re-manipulation and fixation with K-wires should be considered.
We concluded that forearm rotation after a non-reduced diaphyseal both-bone forearm fracture showed a significant improvement after seven years compared to seven months, irrespective of the initial treatment. Children aged below 9 are likely to experience almost full recovery of function, emphasizing that the remaining growth behaves favorably in the long-term.
For reduced diaphyseal both-bone forearm fractures early conversion to a BEC is the preferred treatment, and the ongoing growth contributes to enhancing function over time, irrespective of the initial treatment, even in cases where the fracture secondarily displaces (30%). There should be a low threshold for intramedullary fixation. This is because they have a lower remodeling capacity due to their distance from the growth plate and poorer functional outcomes resulting from constriction, especially when the age is over ten.
Factors to take into consideration when deciding on pediatric forearm fracture treatment are, type of fracture, location of the fracture, and age of the patient. Specific higher risk for malunion are fractures with re-displacement (unstable fractures), fracture with complete initial displacement of the radius, re-fractures, diaphyseal fractures, and bicortical ulnar fractures.

Part VI

Appendices

Dutch summary/ Nederlandse Samenvatting

Hoofdstuk 1. Algemene inleiding en doel van het proefschrift

Bijna de helft van de pediatrische fracturen zijn onderarmfracturen. Deze fracturen bevinden zich in veertien procent van de gevallen rondom de distale radiaire groeischijf, in 65% van de gevallen in de distale metafyse, in 20% van de gevallen in de diafyse, en in één procent van de gevallen in de proximale metafyse. De meerderheid van deze fracturen wordt niet-chirurgisch behandeld met gips. Behandeling van fracturen met gips heeft echter een belangrijk nadeel, aangezien verplaatsing van fracturen optreedt bij 7-39% van de gevallen, wat potentieel kan leiden tot een malunion. Een malunion leidt niet altijd tot functionele beperkingen omdat kinderen een uitstekend vermogen tot remodelering hebben. Het vermogen tot remodelering hangt af van twee cruciale factoren: de afstand van de fractuur tot de groeischijf en de resterende groei die gerelateerd is aan de leeftijd en het geslacht van het kind. Onvoldoende remodelering kan resulteren in verminderde functionele resultaten.

Dit proefschrift heeft als doel inzicht te creëren in het beloop van onderarms fracturen bij kinderen gebaseerd op lange termijn resultaten van prospectieve studies. Het doel van dit proefschrift is daarnaast om handvatten en waar mogelijk richtlijnen te formuleren voor medische professionals met betrekking tot de optimale timing, duur en type behandeling van onderarmfracturen bij kinderen.

Hoofdstuk 2. Below-elbow cast sufficient for the treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children: long-term results of a randomized controlled multicenter trial

Dit hoofdstuk beschrijft een lange termijn follow-up van een gerandomiseerde gecontroleerde studie (RCT) bij kinderen met minimaal verplaatste distale onderarmbreuken. Eén groep kreeg behandeling met een bovenarmspalk, terwijl de andere werd geïmmobiliseerd met een onderarmspalk. De laatste groep meldde een verhoogd comfort, verminderde interferentie in dagelijkse activiteiten en vergelijkbare functionele resultaten bij de follow-up na zeven maanden. Deze studie beoordeelt de uitkomsten bij de follow-up na zeven jaar, met focus op het verlies van onderarmrotatie, het verlies van flexie-extensie van de elleboog en pols in vergelijking met de contralaterale onderarm. Andere onderzochte parameters zijn de QuickDASH-score, ABILHAND-kids vragenlijst, grijpkracht (gemeten met een JAMAR dynamometer) gepresenteerd als een verhouding van de aangedane onderarm tot de contralaterale zijde, en radiologische beoordeling van de hoek van de radius en ulna.

De gemiddelde follow-up duur was 7.3 jaar. Van de oorspronkelijke 66 kinderen die waren opgenomen in de RCT, werden 51 kinderen geëvalueerd bij de lange termijn follow-up, 26 van de 31 patiënten kregen een bovenarmspalk, en 25 van de 35 patiënten kregen een onderarmspalk. Het verlies van onderarmrotatie en secundaire uitkomsten waren vergelijkbaar in de twee behandelingsgroepen. Daarom is ons advies om kinderen met minimaal verplaatste distale onderarmbreuken te behandelen met een onderarmspalk.

Hoofdstuk 3. Do We Need to Stabilize All Reduced Metaphyseal Both-Bone Forearm Fractures in Children with K-wires?

In dit hoofdstuk worden de resultaten beschreven van patiënten met een distale onderarmbreuk waarvoor reductie noodzakelijk was. De bevindingen van een gerandomiseerde studie met een lange termijn follow-up waarbij kinderen willekeurig werden verdeeld voor een behandeling middels een bovenarmspalk (gips) of fixatie met K-draden en een bovenarmspalk (K-draadgroep). De gemiddelde follow-up duur was 6.8 jaar, met 54 deelnemers in de gipsgroep en 51 in de K-draadgroep. De patiënten hadden een gemiddelde leeftijd van negen jaar op het moment van trauma en een gemiddelde scheefstand van de radius en ulna van respectievelijk 25° en 23°. Re-dislocaties kwamen vaker voor bij patiënten die alleen werden behandeld met een bovenarmspalk (19% vs. 7%). Opmerkelijk genoeg werden er geen significante verschillen waargenomen in onderarmrotatie, klinische uitkomstmaten en radiologische bevindingen. Dit suggereert dat -manipulatie en fixatie met K-draden primair moeten worden overwogen bij een distale onderarm fractuur waarbij reductie op de operatie kamer wordt uitgevoerd.

Hoofdstuk 4. Improved forearm rotation even after early conversion to below-elbow cast for non-reduced diaphyseal both-bones forearm fractures in children: a secondary 7.5-year follow up of a randomized trial

In dit hoofdstuk is een analyse gedaan van kinderen met midschacht onderarmbreuken, waarbij geen reductie vereist was. De gemiddelde follow-up duur was 7.3 jaar, 38 van de oorspronkelijke 47 kinderen zijn geïncludeerd. De rotatie verbeterde in beide groepen in de loop van de tijd, 8 graden voor de OAG-groep en 8 graden voor de BAG-groep. Er werd geen verschil waargenomen in PROM's en radiologische angulatie. We concludeerden dat onderarmrotatie na een niet-gereduceerde midschacht onderarmbreuk na 7.3 jaar significant verbeterde in vergelijking rotatie met 7 maanden, ongeacht de initiële behandeling. Kinderen jonger dan negen jaar zullen naar alle waarschijnlijkheid bijna volledig herstellen, ongeacht een eventuele malunion. Bij kinderen boven de leeftijd van negen jaar kwamen een paar ernstige malunions voor, maar zelfs deze remodelleerden bijna allemaal, zonder enig functioneel verlies. Dit benadrukt dat de resterende groei zich gunstig gedraagt op de lange termijn.

Hoofdstuk 5. Does early conversion to below-elbow casting for pediatric diaphyseal both bones forearm fractures adversely affect patient-reported outcomes and range of motion?

Nadat we de niet gereduceerde midschacht onderarmbreuken hebben besproken in Hoofdstuk 4, richten we nu onze aandacht op de groep met midschacht onderarmbreuken die wel reductie vereisen. De belangrijkste vraag die wordt behandeld, is of vroege omzetting naar een onderarmgips de aanbevolen behandeling moet zijn, en of een geaccepteerde secundaire dislocatie leidt tot inferieure klinische resultaten op lange termijn. De beoordeelde uitkomsten komen overeen met die in onze eerdere studies. De gemiddelde follow-up duur was 7.5

jaar en we hebben 97 van de 128 deelnemers geïncludeerd, 47 in de bovenarm gips-groep (BAG) en 50 in de boven/onderarms gips-groep (BAG/OAG). Verlies van onderarmrotatie was 8 graden voor de BAG-groep en 4 graden voor de BAG/OAG-groep, met een gemiddeld verschil van 3.8 graden (p=0.47). De lange termijn follow-up toonde een significante verbetering in onderarmrotatie in beide groepen vergeleken met de rotatie op zeven maanden. In de bovenarm gips-groep was een afname van 27 graden bij twee maanden naar 18 graden bij zeven maanden naar 8 graden bij zeven jaar follow-up. Voor de BAG/OAG-groep van 22 bij twee maanden naar 12 bij zeven maanden naar 4 graden bij zeven jaar follow-up. Er werden geen significante verschillen gevonden tussen groepen wat betreft primaire en secundaire uitkomsten. Dertien patiënten met aanhoudende malunion bij zeven maanden follow-up vertoonden geen klinisch relevante verschillen in functionele resultaten bij lange termijn follow-up vergeleken met kinderen zonder malunion. Het verlies in onderarmrotatie was 5.5 graden voor de malunion-groep vergeleken met 6 graden in de niet-malunion-groep, met een gemiddeld verschil van 0.4 (p=0.92). Concluderend, vroege conversie naar een onderarms gips komt naar voren als de voorkeursbehandeling, en de voortdurende groei en remodellering dragen bij aan het verbeteren van de functie in de loop van de tijd, ongeacht de initiële behandeling, zelfs in gevallen waarbij de fractuur secundair verplaatst is.

Hoofdstuk 6. Systematic review on the functional outcome after treatment of a traumatic bowing fracture of the lower arm in children

Dit hoofdstuk zal een minder voorkomende pediatrische fractuur behandelen, bekend als de bowings breuk van de onderarm. Vaak wordt deze over het hoofd gezien en dit kan resulteren in verminderde rotatie van de onderarm. Onze systematische review toonde aan dat reductie van dit type breuk over het algemeen goed werd verdragen, maar ook een direct positief effect had en bijdroeg aan een sneller herstel van de functie.

De acceptabele mate van bowing zonder verlies van functie blijft onduidelijk. Echter, gezien de minimale complicaties die zijn waargenomen en de positieve resultaten die geassocieerd worden met reductie, het advies is om reductie te overwegen bij alle significante bowings breuk van de onderarm met een rotatiebeperking.

Hoofdstuk 7. What is the acceptable angulation for most common forearm fractures in children?

Het komende hoofdstuk omvat een systematische review gericht op de acceptabele angulatie van de meest voorkomende onderarmbreuken bij kinderen. Het kind skelet wordt gekenmerkt door groei waardoor meer angulatie geaccepteerd kan worden. We hebben 185 artikelen in onze analyse opgenomen. Inbegrepen breuk locaties zijn; breuken rondom de distale radiaire groeischijf, de distale metafyse, de diafyse van de onderarm. De verschillende fractuurpatronen omvatten; bowing en complete breuken. Deze review toont een trend, waarbij voor patiënten jonger dan 10 jaar een hogere tolerantie voor fractuur angulatie kan worden aanvaard dan in

de huidige richtlijnen. Voor patiënten van 10 jaar en ouder wordt daarentegen doorgaans een minder acceptabele angulatie geadviseerd dan in de huidige richtlijnen. De literatuur concludeert dat 14-24 graden acceptabel is voor alle distale radius breuken waarbij de groeischrijf betrokken is, 12-27 graden acceptabel is voor distale radius breuken, 9-21 graden acceptabel is voor distale onderarmbreuken, 9-21 graden is acceptabel voor midschacht breuken van de onderarm en 19-37 graden voor breuken van de radiaire nek.
Vergeleken met de huidige richtlijnen suggereren onze gecombineerde literatuur review en deskundigen opinie dat er voor de meest voorkomende typen onderarmbreuken bij kinderen meer angulatie geaccepteerd zouden kunnen worden dan wat in de huidige richtlijnen wordt geadviseerd. Het advies is om de richtlijnen aan te passen waar nodig en dit in de klinische praktijk te implementeren.

Hoofdstuk 8. Predictors for a limitation of pro-supination after pediatric both-bone forearm fractures: the 7-year follow-up of 316 patients.
Dit laatste hoofdstuk behandelt twee fundamentele vragen: ten eerste, welke factoren geassocieerd zijn met beperkingen in pro-supinatie op lange termijn, en ten tweede, of geaccepteerde re-dislocaties leiden tot inferieure functionele en radiografische uitkomsten op lange termijn. De studie richt zich op patiënten met distale en midschacht breuken van de onderarm, met een minimum follow-up van vier jaar. Patiënten zijn initieel in verschillende RCT's geïncludeerd, zoals degene die randomiseert tussen een onderarm- en bovenarmgips (OAG/BAG) voor niet gedisloceerde distale breuken, diegene die randomiseert tussen BAG en vroege conversie naar OAG voor stabiele midschacht breuken, en één of twee intra medullaire pinnen voor instabiele midschacht breuken. Onze primaire uitkomstmaat was langdurige functionele beperking (beperking in pro-supinatie en QuickDASH score). Andere geanalyseerde factoren zijn leeftijd bij trauma, breuk locatie, breuk type (greenstick versus bicorticaal), volledige initiële verplaatsing van radius of ulna, re-dislocatie, (onbehandelde) re-dislocatie en herhaalde breuk. De studie includeerde 316 van de 410 deelnemers (77%), met een gemiddelde follow-up van 7.2 jaar. Er waren 149 midschacht breuken (46%) en 167 distale breuken (54%). De gemiddelde leeftijd bij trauma was 8.1 jaar. Analyse toonde aan dat voorspellers voor beperkingen in pro-supinatie van ≥15° op lange termijn volledige initiële verplaatsing van de radius, herhaalde breuk, midschacht locatie van de breuk en bicorticale ulnaire breuk waren. Een voorspeller voor een QuickDASH-score van ≥20 punten was een bicorticale ulnaire breuk. Er waren geen klinisch relevante verschillen op lange termijn tussen patiënten met geaccepteerde re-dislocaties versus die met een goede stand.
Behandeloverwegingen voor distale onderarms breuken zijn; de remodellerings potentie, met name bij kinderen <10jaar. Als re-dislocatie optreedt, zou overwogen moeten worden de re-dislocatie te accepteren of een re-manipulatie uit te voeren (± K-draad fixatie), gebaseerd op het verwachte remodelleerpotentieel afhankelijk van de leeftijd. Behandeloverwegingen voor midschacht onderarms breuken zijn; 30% van de stabiele breuken disloceert alsnog na gesloten

reductie in het gips. Breuken op deze locatie tonen minder remodellering potentieel, daarom moet aanvullende intra medullaire stabilisatie worden overwogen met name bij kinderen ouder dan tien jaar.

Hoofdstuk 9. Algemene discussie

Dit hoofdstuk presenteert de algemene discussie. In dit hoofdstuk worden de belangrijkste bevindingen van het proefschrift samengevat, verder worden de klinische implicaties en toekomstperspectieven besproken.

Conclusie en aanbevelingen

Deze scriptie heeft een uniek inzicht geboden in het gedrag van het kind skelet met betrekking tot onderarms breuken dankzij lange termijn prospectieve studies. Kinderen met groeipotentieel tonen uitstekende remodellering van malunions.

Met uitzondering van bowing breuken, waar de heersende consensus is om alle significante bowing breuken van de onderarm bij kinderen met rotatiebeperking te reduceren ze daarna kort met gips te behandelen.

Minimaal verplaatste distale botbreuken van de onderarm moeten worden behandeld met een onderarmgips. Bij initieel verplaatste breuken, kwamen re-dislocaties vaker voor bij patiënten die na repositie van de breuk zonder k-draad fixatie werden behandeld in gips. Bij kinderen boven 10 jaar moet daarom worden overwogen om de breuk na een (re-)manipulatie te fixeren met k-draden, omdat zij minder remodellering capaciteit vertonen.

Bij kinderen een midschacht breuk waarbij geen reductie noodzakelijk was, liet de onderarmrotatie duidelijk een verbetering liet zien na zeven jaar in vergelijking met zeven maanden, ongeacht de initiële behandeling. Kinderen jonger dan 9 jaar zullen naar verwachting bijna volledig herstellen, waarbij wordt benadrukt dat de resterende groei zich gunstig gedraagt op de lange termijn.

Voor gereduceerde midschacht breuken van beide botten van de onderarm is vroege conversie naar een onderarmgips de voorkeursbehandeling, waarbij de resterende groei bijdraagt aan een betere functie in de loop van de tijd, ongeacht de initiële behandeling, zelfs in gevallen waarbij de fractuur secundair disloceerd (30%). Intramedullaire fixatie moet laagdrempelig worden overwogen. Deze groep breuken heeft lagere remodellering capaciteit vanwege de afstand tot de groeischijf, met een slechtere functionele uitkomst als gevolg, vooral bij een leeftijd ouder dan tien jaar.

Factoren om rekening mee te houden bij het kiezen van de behandeling van onderarm breuken bij kinderen zijn; het type, de locatie en de leeftijd van de patiënt. Specifieke hogere risico's voor malunion zijn breuken met re-dislocatie (instabiele breuken), breuken met volledige initiële verplaatsing van de radius, re-fracturen, midschacht breuken en bicorticale ulna breuken.

PhD Portfolio

Education

2023-2024	Fellowship Orthopaedics Oncology, FMC, Adelaide, Australia
2022-2023	Fellowship Orthopaedics, trauma&arthroplasty, FMC, Adelaide, Australia
2006-2012	Study of Medicine, Erasmus MC, Rotterdam, the Netherlands, Cum Laude
2003-2006	Bachelor Biomedical Science, Utrecht University, the Netherlands
2012	Elective internship Orthopedics, RdGG, Delft, the Netherlands
2010	Research internship, Groote Schuur Hospital, Cape Town, South-Africa

Medical Experience

2022-2024	Fellowship Orthopaedic surgery, FMC, Adelaide, Australia
2022	Orthopedic resident, Spaarne Gasthuis, Hoofddorp, the Netherlands
2020-2022	Orthopedic resident, Noordwest Ziekenhuisgroep, Alkmaar, the Netherlands
2018-2020	Orthopedic resident, Spaarne Gasthuis, Hoofddorp, the Netherlands
2016-2018	Orthopedic resident, AUMC, Amsterdam, the Netherlands
2014-2016	Surgical resident, Spaarne Gasthuis, Haarlem, the Netherlands
2012-2014	House officer at general surgery, MCH, The Hague, the Netherlands

Research Experience

2010	Draw for an article; Linde Musters, Monique Walenkamp, Prof. Nicol, Esther van Lieshout, Oscar van Waes. Validation of the American Association for the Surgery of Trauma Organ Injury Scale (AAST-OIS) grading system in liver trauma patients in terms of Hospital Length of Stay, operative rate and mortality.
2012	Medical-ethical board application; Assessing the learning curve of anterior supine intramuscular total hip arthroplasty, L Musters, M Benard, Dr. SBW Vehmeijer.
2012	Medical-ethical board application; Outcome of minimally invasive anterior supine intramuscular total hip arthroplasty, L Musters, YM Den Hartog, M Benard, Dr. SBW Vehmeijer.

Publications

2024	**What is the acceptable angulation for most common forearm fractures in children?** Submitted with JBJS June 2024
2024	**Which factors are associated with a long-term functional impairment after a pediatric both-bone forearm fracture?** Submitted with AOTS June 2024
2024	**Does Early Conversion to Below-elbow Casting for Pediatric Diaphyseal Forearm Fractures Adversely Affect Patient-reported**

Outcomes and ROM?

Linde Musters, Kasper C. Roth, Leon W. Diederix, Pimp P. Edomskis, Joyce L. Benner, Max Reijman, Denise Eygendaal, Joost W. Colaris. CORR. 2024.

2023 **Improved forearm rotation even after early conversion to below-elbow cast for non-reduced diaphyseal both-bones forearm fractures in children: a secondary 7.5-year follow up of a randomized trial.**

Musters L, Diederix LW, Edomskis PP, Roth KC, Benner JL, Kraan GA, Allema JH, Reijman M, Eygendaal D, Colaris JW. Acta Orthop. 2023 Oct 6;94:493-498.

2022 **Do We Need to Stabilize All Reduced Metaphyseal Both-bone Forearm Fractures in Children with K-wires?**

Diederix LW, Roth KC, Edomskis PP, Musters L, Allema JH, Kraan GA, Reijman M,Colaris JW. Clin Orthop Relat Res. 2022 Feb 1;480(2):395-404.

2021 **Below-elbow cast sufficient for treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children: long-term results of a randomized controlled multicenter trial.**

Musters L, Diederix LW, Roth KC, Edomskis PP, Kraan GA, Allema JH, Reijman M, Colaris JW. Acta Orthop. 2021 Aug;92(4):468-471.

2019 **Permeability of surgical gloves after handling PMMA bone cement.**

Musters L. NTvO, Maart 2019, Vol. 26, Nummer 1

2017 **Case Report: SPECT/CT as the New Diagnostic Tool for Specific Wrist Pathology.**

Musters L, Broek TM, Kraan GA J Arthritis. 2017. 6:246.

2017 **Systematic Review on the Functional Outcome After Treatment of a Traumatic Bowing Fracture of the Lower Arm in Children.**

Musters L, Colaris J.W. J Trauma Treat. 2017;6(3):384. E

2015 **Dislocation of the proximal tibiofibular joint, do not miss it.**

van Wulfften Palthe AF, Musters L, Sonnega RJ, van der Sluijs HA. BMJ Case Rep. 2015 Dec. 1;2015.

2014 **Exceptional localization of an ectopic parathyroid adenoma at the level of the hyoid bone.**

Musters L, van Ginhoven TM, Smit C. BMJ Case Rep. 2014 Jun 1;2014.

Oral Presentations

1-6-2024 **Scientific Meeting Flinders Medical Centre**

Presentation of my entire thesis.

16-2-2024 **SA/NT Branch Scientific Papers DAY AOA, Adelaide;** Long-term follow-up shows comparable outcomes for early conversion to a belowelbow cast compared to only an AEC for pediatric reduced diaphyseal both bone forearm fractures.

19-5-2022 **NOV Annual Conference;** Does Early Conversion to Below-elbow Casting for Pediatric Diaphyseal Forearm Fractures Adversely Affect Patient-reported Outcomes and ROM?

4-11-2021 **Trauma days conference, Amsterdam;** Below-elbow cast sufficient for treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children: long-term results of a randomized controlled multicenter trial.

21-9-2021 **Anual meeting Orthopedics, Spaarne Gasthuis;** Below-elbow cast sufficient for treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children: long-term results of a randomized controlled multicenter trial.

21-5-2021 **NOV Annual Conference;** Below-elbow cast sufficient for treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children: long-term results of a randomized controlled multicenter trial.

19-5-2021 **FESSH, Budapest;** Below-elbow cast sufficient for treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children: long-term results of a randomized controlled multicenter trial.

Poster Presentations

14-12-2022 **IOTA 1st Triennial Meeting, Amsterdam;** Long term results of a multi center RCT on early conversion to below elbow cast as treatment for stable diaphyseal both-bone forearm fractures in children after reduction.

8-11-2021 **Orthopaedics science conference, Vienna;** 7.3-year FU confirms safe early conversion to below elbow cast for non-reduced diaphyseal forearm fractures of both bones in children.

Courses/ organizational

2023	Good clinical practice
2022	Scientific Integrity Course, Erasmus MC
2022	AO Advances in trauma
2022	ATLS refresher
2021	DSATC
2021	Stryker FRCS Preparation Course Virtual Series
2019	ATLS
2019	Advanced trauma
2019	AO approaches and fracture care

2019	Boerhaave Radiation Course
2018	Basic hospital management
2018	19th Groningen Dissection Course
2016	Knee Arthroscopy
2016	OTC basic trauma course
2015	CASH course
2015	Course Communicational Skills
2015	Basic surgical anatomy of the wrist and groin
2013	ATLS provider course

Curriculum vitae

ABOUT THE AUTHOR

Linde was born on the 13th of September in Nijmegen, the Netherlands. She grew up in Tiel where she attended secondary school at the Linge college. After graduating in 2003, she started Biomedical Science at the University of Utrecht. After gaining her bachelor's degree she enrolled in Medical School at the Erasmus University of Rotterdam. She expanded her horizon with a research/clinical rotation at the Groote Schuur Hospital in Cape Town South Africa.

During the finalization of her medical degree, she started her journey in research by publishing her first case reports. Before commencing her training as an Orthopedic Surgeon, Linde served as a house officer at the Westeinde Hospital in The Hague in 2012. Her official training started at the VU Medical Centre in Amsterdam in 2014 under the guidance of Dr. Hans van de Sluijs. She furthered her expertise as a General Surgical resident at the Spaarne Gasthuis in Hoofddorp under Dr. G. Akkersdijk.

During her training, she simultaneously started her PhD journey at the Erasmus Medical Centre of Rotterdam with Dr. J. Colaris, Prof D. Eygendaal and M. Reijman.

Her residency took her to several locations; the Spaarne Gasthuis in Hoofddorp with Dr. A. van Noort, Amsterdam University Medical Centers with Prof. G. Kerkhoffs and NoordWest Hospital in Alkmaar with Dr. B.Burger and Dr. L.C.Keijser.

Upon completion of her training in August 2022, Linde secured a trauma/arthroplasty fellowship in Adelaide, Australia at Flinders Medical Center under the mentorship of Prof. Dr. R.L. Jaarsma. Currently, Linde continues to thrive in Australia, doing an extended fellowship focusing on oncology and revision arthroplasty with Dr. L. Johnson and Dr. J. Jagiello.

Linde has returned to The Netherlands in August 2024, accompanied by her beloved sons Dex, Otis and Matéo and husband Albis Beije Ramirez, where she further specializes in knee arthroplasty and ligamentous reconstruction and sports under the guidance of Gie Auw-Yang and Martijn van Dijk at the St Antonius Hospital in Utrecht.

Abbreviations

ABBREVIATIONS

AEC	above-elbow cast
BEC	below-elbow cast
CI	confidence interval
DASH	disabilities of the arm, shoulder and hand
ROM	range of motion
AO	arbeitsgemeinschaft für osteosynthesefragen
RCT	randomized controlled trial

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