

Forearm Fractures in Children



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Fractura antebrachii op kinderleeftijd

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Fractura antebrachii op kinderleeftijd

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PART I

GENERAL INTRODUCTION

CHAPTER 1

Introduction and outline of the thesis

INTRODUCTION AND OUTLINE OF THE THESIS

The forearm consists of the radius and ulna which are connected by the proximal and distal radioulnar joints, the interosseous membrane and several muscles. Forearm rotation, consisting of pronation and supination, is a rotatory motion of the radius around the ulna in combination with subtle translation¹. The longitudinal axis of the forearm is considered to pass through the centre of the radial head proximally and through the ulnar fovea at the base of the ulnar styloid distally².

Forearm rotation is commonly used in daily life; whereas pronation is used for writing and typing, movements such as perineal hygiene and accepting monetary change require supination. In children up to the age of 15 years, pronation of 50-80 degrees and supination of 80-120 degrees are considered normal³. Furthermore a limitation of forearm rotation only affects daily activities if pronation or supination is less than 50 degrees⁴, because the ipsilateral shoulder can compensate mild limitation of pronation by abduction and internal rotation, and mild limitation of supination by adduction and external rotation.

In a number of pathologies forearm rotation can be limited, such as following a forearm fracture. Forearm fractures represent one of the most common fractures in children; a distinction is made between fractures of the radius or the ulna only, and fractures of both the radius and ulna. Furthermore, a differentiation is made between incomplete fractures typical for children (torus, greenstick and bowing) and complete fractures that occur in children as well as in adults. The treatment of these both-bone forearm fractures depends on anatomical location (proximal metaphysis, distal metaphysis or diaphysis) and fracture displacement (minimally displaced or severely displaced).

Metaphyseal both-bone fractures of the distal forearm

Minimally-displaced metaphyseal both-bone fractures of the distal forearm are divided in torus fractures, and the more severe greenstick and complete fractures. The first group is usually treated with a below-elbow cast (**BEC**) for pain reduction. The second group is generally treated with an above-elbow cast (**AEC**) to prevent fracture displacement⁵⁻⁸. Two studies that randomised between AEC and BEC for metaphyseal fractures of the distal forearm in children, concluded that both casts

are effective to maintain reduction of the fracture, while BEC interfered less with daily activities⁹⁻¹⁰. One of these latter studies reported a significant difference in the arc of elbow motion in favour of the BEC group at time of cast removal and at final examination¹⁰. However, none of these studies included only both-bone forearm fractures, even though these fractures are notorious for instability and dislocation^{9,10}. Therefore, we designed the first randomised study to compare BEC and AEC for the treatment of exclusively minimally-displaced metaphyseal both-bone fractures of the distal forearm in children. (**Chapter 2**)

Severely displaced metaphyseal both-bone fractures of the distal forearm need to be reduced and stabilised. After reduction, the method of stabilisation ranges from BEC only, to percutaneous pinning with Kirschner wires in combination with an AEC^{5,9,10,12-19}. Re-displacement of the fractures treated without percutaneous pinning has been described in 7-91% of children^{5,13,17-23} and such re-displacement can lead to malunion with reduced functional and cosmetic results^{24,25}. In case of re-displacement the clinician is often confronted with a treatment dilemma, i.e. whether to accept some degree of re-displacement or to perform a secondary reduction of the fracture. Several randomised studies compared treatment modalities for a combination of single-bone and both-bone forearm fractures in children. Two studies randomised between AEC and BEC and found the highest percentage of re-displacement in the AEC group, which could be explained by poor cast moulding^{9,10}. Two other studies randomised between AEC with or without percutaneous pinning; re-displacement appeared only in the group without percutaneous pinning and was 21% in one study and 39% in the other^{15,16}. Although these studies were well performed, none of them distinguished between fractures of the radius or ulna only, and fractures of both the radius and ulna, whereas the latter are often highly unstable^{9,11,23}. Therefore, we performed a multicentre study designed for only displaced metaphyseal both-bone fractures of the distal forearm in children, which were apparently stable after reduction in the operation room. After randomisation the fractures were treated with AEC alone or by a combination of percutaneous pinning with AEC. (**Chapter 3**)

Diaphyseal both-bone forearm fractures

Treatment modalities for diaphyseal both-bone forearm fractures in children are casting without reduction, closed reduction with casting, closed reduction with intramedullary nailing, and open reduction with intramedullary nailing or plate fixation.

Most minimally-displaced fractures and displaced fractures that are stable after reduction can be treated successfully with an AEC for 6-9 weeks. This AEC is often converted to a BEC in the last weeks of treatment^{3,8,26-34}. Although many of these fractures heal without complications, limitation of pronation and supination can occur. An average limitation of 20 degrees in about 15% of children has been reported^{30,35,36}. This limitation of pronation/supination after both-bone diaphyseal forearm fractures in children seems to be caused by both malunion of the radius and/or the ulna, and a contracture of the surrounding soft tissue³⁶⁻⁴¹. Early conversion to BEC in the treatment of these fractures could potentially influence the limitation of pronation and supination in two opposing ways. On the one hand, BEC does not immobilise the elbow and could therefore result in displacement of the fracture, malunion and consequently more limitation. On the other hand, BEC allows free movement of the elbow that could result in fewer contractures of soft tissue and consequently less limitation. Nevertheless, the influence of AEC and BEC on limitation of pronation/supination remains unclear. Therefore, we aimed to clarify the role of AEC and BEC on limitation of pronation and supination in both-bone diaphyseal forearm fractures that were minimally-displaced or stable after reduction. **(Chapters 4 and 5)**

Displaced diaphyseal both-bone forearm fractures that are unstable after reduction are generally stabilised by two intramedullary nails. As an alternative, the possibility of single-bone fixation in both-bone forearm fractures combined with a complementary cast has been studied^{34,42-50}. Single-bone intramedullary fixation in both-bone forearm fractures offers both advantages and disadvantages. Although insertion and removal of only one nail can reduce operation time and complications, the bone without fixation has a tendency to displace necessitating immobilisation in a cast. To date, only one study (including 20 children, no controls) has prospectively investigated single-bone fixation in both-bone forearm fractures⁴⁵, whereas others used a retrospective design^{34,42-46,49-52}. Most studies concluded that

single-bone intramedullary fixation of both-bone diaphyseal forearm fractures in children is a safe and efficacious option with good functional and radiological results^{34,42-46,49-52}. However, these results were based on a selection of children who sustained a both-bone forearm fracture that remained aligned and stable after single-bone fixation^{34,42-46,49-52}. Therefore, to systematically compare the value of the two types of fixation, we set up a randomised study that compared single-bone with both-bone intramedullary fixation. (**Chapter 6**)

Fracture displacement

While many children who sustained a both-bone forearm fracture are treated with cast, fracture displacement may occur and has been reported in 7-91% of the patients^{5,13,17-23}. This displacement might lead to malunion with reduced functional and cosmetic results^{24,25}. Despite the high frequency of fracture displacement in cast, the risk factors have not yet been analysed in large prospective studies^{10,17,19,23,53-55}. Therefore, we conducted a study to identify risk factors of fracture displacement in cast for both-bone forearm fractures in children. (**Chapter 7**)

Limitation of forearm rotation

As mentioned above, both-bone forearm fractures in children can be complicated by a limitation of forearm rotation. Therefore, measurement of pronation and supination is important for clinical decision-making and outcome evaluation for these fractures. Many devices have been developed to measure pronation and supination of the forearm; these include gravity-dependent methods, tubular handles, voltage gated sensors, and measurements of digital photographs^{29,56-61}. For many of these devices, reliability is fair to excellent, as expressed by intraclass correlation coefficients⁶² ranging from 0.78 to 0.99 for intrarater reliability^{56,58,61} and from 0.72 to 0.98 for interrater reliability^{56,57,59,61}. However, the above-mentioned devices are complex, difficult to use in standard clinical care, and may intimidate young children. Therefore, forearm rotation in children is still generally evaluated by visual estimation or conventional goniometry. The reliability of these two methods was studied in paediatric patients that had previously sustained a forearm fracture. (**Chapter 8**)

Limitation of forearm rotation can be caused by pathology of either the bones or soft tissue in the forearm. Although a malunion is frequently mentioned as the main cause of limitation of forearm rotation^{25,37,63-68} there is no consensus on this. Whereas several studies described limitation without a malunion^{35,36,67}, others mentioned malunions without limitation⁶⁹ or persistent limitation after a corrective osteotomy with restoration of anatomical alignment⁷⁰⁻⁷². Other bone-related causes of limitation are a synostosis, or an impingement between radius and ulna^{66,67,73}. Although the exact role of soft tissue involvement in limitation of rotation is still unclear^{41,74-78}, contractures of the interosseous membrane might play a more significant role than contractures of capsules of wrist and elbow^{69,79}. Thus, many other clinical factors associated with limitation of forearm rotation have not yet been explored. However, knowledge on these factors can contribute to better clinical care by change of treatment (when required), as well as more detailed information provided to parents and children. Therefore, we analysed the relation between several clinical factors and limitation of forearm rotation in children who sustained a both-bone forearm fracture. **(Chapter 9)**

Malunion, as cause of limitation of forearm rotation, was previously studied in human upper-extremity cadaver specimens. Artificially created angular deformities of the forearm of 10 degrees or less resulted in minimum limitation of pronation and supination while 20 degrees of angulation caused an important loss^{66,67}. Others compared these experimental results with data obtained from clinical and radiographic examination and found that the experimental results predicted the clinical loss of pronation/supination relatively well⁸⁰. Because these findings are highly relevant for clinicians' decision-making regarding whether to accept some degree of re-displacement or to perform a secondary reduction of the fracture, we compared pronation/supination and angular malalignment in a prospective clinical study. **(Chapter 10)**

Unravelling the exact cause of limitation after a both-bone forearm fracture remains a diagnostic challenge. Although conventional radiographs can be used to detect angular and translational malunions or synostosis, it is difficult to reveal subtle rotational malunions and bony impingement with this method. Evidently, contractures of the interosseous membrane are not detectable on conventional radiographs. To clarify the causes of limitation of pronation/supination after both-

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bone forearm fractures in children, we performed a three-dimensional imaging study with computed tomography (CT) and magnetic resonance imaging (MRI) to evaluate the role of rotational malunion, bony impingement and contractures of the interosseous membrane. (**Chapter 11**)

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PART II

METAPHYSEAL BOTH-BONE FRACTURES OF THE DISTAL FOREARM

CHAPTER 2

Below-elbow cast for metaphyseal both-bone fractures of the distal forearm in children: *a randomised multicentre study*

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ABSTRACT

Introduction: Minimally displaced metaphyseal both-bone fractures of the distal forearm in children are often treated with an above-elbow cast (AEC). Treatment with a below-elbow cast (BEC) could give more comfort, but might lead to fracture displacement reducing pronation and supination. Because this has not been systematically investigated, we set up a randomised multicentre study. The purpose of this study was to find out whether BEC causes equal limitation of pronation and supination but with higher comfort level, compared with AEC.

Patients and methods: In four hospitals, consecutive children aged < 16 (mean 7.1) years with a minimally displaced metaphyseal both-bone fracture of the distal forearm were randomised to 4 weeks BEC (n=35) or 4 weeks AEC (n=31). Primary outcome was limitation of pronation and supination 6 months after initial trauma. The secondary outcomes were cast comfort, limitation of flexion/extension of wrist/elbow, complications, cosmetics, complaints, and radiological assessment.

Results: A group of 35 children received BEC and 31 children received AEC. All children attended for the final examination at a mean follow-up of 7.0 months (range 5.0-11.6 months). Limitation of pronation and supination 6 months after initial trauma showed no significant difference between the two groups [4.4° (± 5.8) for BEC and 5.8° (± 9.8) for AEC]. Children treated with BEC had significantly higher cast comfort on a visual analogue scale [5.6 (± 2.7) vs. 8.4 (± 1.4)] and needed significantly less help with dressing (8.2 vs. 15.1 days). Six complications occurred in the BEC group and 14 in the AEC group. Other secondary outcomes were similar between the two groups.

Conclusions: Children with minimally displaced metaphyseal both-bone fractures of the distal forearm should be treated with a below-elbow cast.

INTRODUCTION

Metaphyseal both-bone fractures of the distal forearm are among the most common injuries in childhood. The minimally displaced fractures are divided in torus fractures and the more severe greenstick and complete fractures. The first group is usually treated with a below-elbow cast (BEC) for comfort. The second group is usually treated with an above-elbow cast (AEC) to prevent fracture displacement¹⁻⁴.

An AEC immobilizes both wrist and elbow that potentially stabilizes the fracture more than immobilization of the wrist only using a BEC. Less fracture stabilization can result in displacement of the fracture leading to malunion, and limitation of pronation and supination. However, AEC can cause more interference with daily activities and give more discomfort than BEC.

Two studies that randomised between AEC and BEC for metaphyseal fractures of the distal forearm in children, concluded that both casts are effective to maintain reduction of the fracture, while BEC interfered less with daily activities^{5,6}. One of these studies reported a significant difference in the arc of elbow motion in favour of the BEC group at time of cast removal and at final examination⁶. None of these studies included only both-bone forearm fractures, although these fractures are notorious for instability and dislocation^{5,7}. Therefore, we designed the first randomised multicentre study to compare BEC and AEC for the treatment of exclusively minimally displaced metaphyseal both-bone fractures of the distal forearm in children. The purpose of this study was to find out whether BEC causes equal limitation of pronation and supination but with higher comfort level, compared with AEC.

PATIENTS AND METHODS

Trial design and participants

A multicentre randomised trial was performed on consecutive children with a minimally displaced metaphyseal fracture of the radius and ulna, who visited the emergency department of one of four participating hospitals. The participating hospitals were: Erasmus Medical Center (Rotterdam), HAGA Hospital (The Hague), Reinier de Graaf Hospital (Delft) and Sint Franciscus Hospital (Rotterdam). The

regional medical ethics committee approved the study and it was registered in ClinicalTrials.gov (NCT00397995). Informed consent was obtained for participation from all the parents and from children aged ≥ 12 years.

Children aged < 16 years with a metaphyseal both-bone fracture of the distal forearm were invited to participate (Figure 1).



Figure 1. Posteroanterior and lateral radiographs of a metaphyseal both-bone fracture of the distal forearm in a child.

The exclusion criteria were: 1) buckle fractures of both the ulna and radius, 2) fracture sustained longer than one week, 3) a severe open fracture (Gustilo II and III) (8), 4) a relapse fracture in the same location, and 5) need for reduction according to *a priori* defined criteria (Table 1).

The primary outcome measure was limitation of pronation and supination 6 months after the fracture. The secondary outcome measures were cast comfort, limitation of flexion and extension of wrist and elbow, complications, cosmetics, complaints and radiological assessment.

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

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

Procedures

The included fractures were randomised between 4 weeks of BEC or 4 weeks of AEC. All casts were applied in neutral position and non-circumferential. All children received a sling for at least 1 week. The children were clinically and radiologically evaluated at 1 and 4 weeks after initial trauma by a resident, supervised by an attending orthopaedic or trauma surgeon. A specialist of plaster revised the cast after 1 week. Where necessary, the fractures were reduced during the period of casting according to the initial reduction criteria (Table 1). Finally, the cast was removed 4 weeks after initial treatment.

One independent orthopaedic surgeon examined all children 2 and 6 months after initial trauma, and measured flexion and extension of wrist and elbow in combination with pronation and supination of both arms. This technique was standardised with the use of a 180° goniometer constructed of clear, flexible plastic with 2 movable arms of 30 cm. Pronation and supination were scaled with a previously used grading system⁹.

Patients with at least 30° of functional impairment at the 2-month examination received a referral for physiotherapy. To evaluate the comfort of the cast a visual analogue scale (VAS) was used; the highest score indicating maximal comfort. In addition, a questionnaire previously used in a similar group of children, evaluated difficulties with 7 daily activities during the period of casting⁶.

Six months after the initial trauma, final radiographs were taken. Both the parents

and the orthopaedic surgeon completed a VAS cosmetics (maximum score indicating best cosmetics) of the fractured arm. In the same consultation, complaints of the fractured arm were documented using a modified grading system. This grading system combines limitation of pronation and supination with complaints in daily life or during strenuous activities. This system was previously used in a similar group of children¹⁰.

The parents completed the ABILHAND-Kids questionnaire¹¹, which is a measure of manual ability for children with upper-limb impairments. The scale is validated for cerebral palsy children and measures a child's ability to manage daily activities that require the use of the upper limbs; the maximum score is 42.

The independent orthopaedic surgeon measured the sagittal and radioulnar angulation of the fracture on the radiographs at three moments, i.e. directly after trauma, after removal of the cast, and 6 months post trauma. The mean and standard deviation (SD) of the sagittal and radioulnar angulation were calculated to determine the primary displacement, re-displacement during the period of casting, and the final displacement at 6 months. To assess the interrater reproducibility an independent trauma surgeon re-measured the sagittal and radioulnar angulation of the fracture of 45 children.

Randomisation and masking

An independent physician randomised the children by sealed envelopes with varied block sizes. A surgeon treated the children during the first 4 weeks without masking. One independent orthopaedic surgeon examined all children 2 and 6 months after the initial trauma without masking. Both the independent orthopaedic surgeon and independent trauma surgeon measured the radiographs with masking.

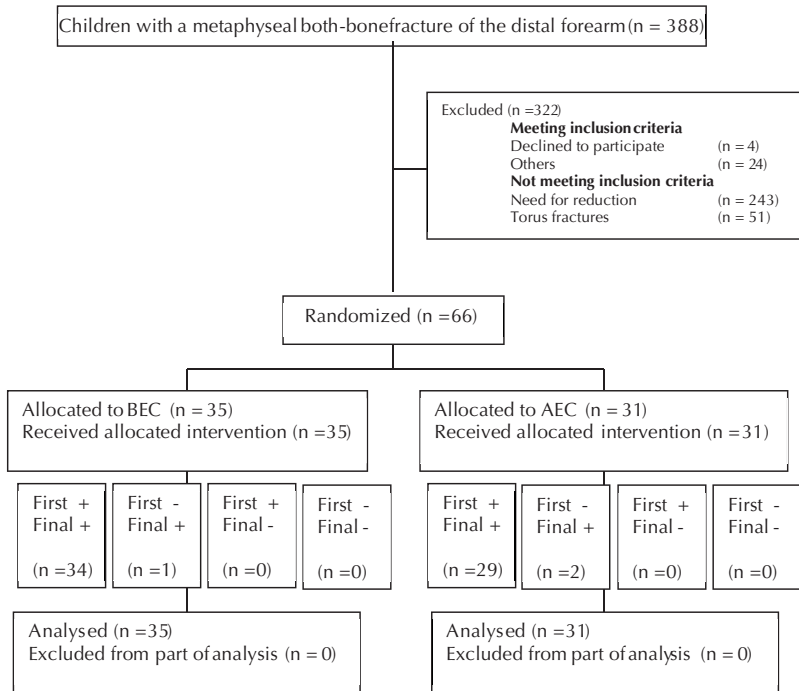
Statistical Methods

To assess the required number of children, an equivalence test was used to demonstrate the similarity of pronation and supination in both groups. Equivalence between the two groups was defined as a maximum of 10° difference in pronation or supination. Using an *a priori* calculation it was determined that, with a power of 82%, a significance of 0.05 and a SD of 15°, the two groups should consist of ± 30 children each. First 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).

Data were analysed using linear regression analysis. If necessary, adjustments were made for unbalanced covariates. Differences between the two groups (BEC vs. AEC) for the secondary outcome measures were analysed using one-way ANOVA to correct for multiple comparisons (Bonferroni). Statistical analyses were performed with SPSS version 17.0 (SPSS Inc., Chicago, USA).

RESULTS

Between January 2006 and August 2010 a total of 66 children were included from four hospitals. Of these, 35 children received BEC and 31 children received AEC (Figure 2).



n = number of children; AEC = above elbow cast; BEC = below elbow cast; First: first examination; Final: final examination; + : examined; - : not examined.

Figure 2. Flowchart of enrollment in the study.

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Table 2 presents the baseline characteristics of the total study population and per randomisation. All children attended for the final examination at a mean follow-up of 7.0 months (range 5.0-11.6 months).

Table 2. *Baseline characteristics of the study population.*

	Total	BEC	AEC
Number	66	35	31
Age in years at time of fracture: mean (SD)	7.1 (\pm 3.5)	7.8 (\pm 3.6)	6.3 (\pm 3.3)
Gender, % male	56.1	48.6	64.5
Dominant arm fractured, %	30.3	25.7	35.5
Type fracture radius, %			
Torus	7.6	2.9	12.9
Greenstick	84.8	88.5	80.6
Complete	7.6	8.6	6.5
Type fracture ulna, %			
Torus	19.7	20.0	19.4
Greenstick	77.3	77.1	77.4
Complete	3.0	2.9	3.2

BEC: below-elbow cast. AEC: above-elbow cast; SD = standard deviation; No significant differences between BEC and AEC groups.

Table 3 presents data on the primary outcome measure. No significant differences in limitation of pronation and supination were found either after cast removal or at 6 months post fracture.

Table 4 presents data on the secondary outcome measures. The group treated with BEC showed significantly higher VAS comfort and needed less help with dressing compared with the AEC group (8.2 vs. 15.1 days: $p=0.024$). Six complications occurred in the BEC group and 14 complications occurred in the AEC

Table 3. *Limitation of pronation and supination of fractured arm.*

	BEC	AEC
Two months after the fracture		
None	15	10
1-10 degrees	10	8
11-20 degrees	3	6
21-30 degrees	3	2
>31 degrees	3	3
Total	34	29
Mean limitation / SD (degrees)	9.1 (\pm 12.2)*	10.7 (\pm 12.2)*
Six months after the fracture		
None	17	18
1-10 degrees	14	7
11-20 degrees	4	3
21-30 degrees	0	2
>31 degrees	0	1
Total	35	31
Mean limitation in degrees (SD)	4.4 (\pm 5.8)*	5.8 (\pm 9.8)

*BEC: below-elbow cast. AEC: above-elbow cast; Data are presented as numbers (unless otherwise indicated).

SD = standard deviation.

* No significant difference in mean limitation of pronation and supination between both groups.

Three children missed the two-month examination.

group. These complications consisted of displacement in the cast in 5 children in the BEC group and in 10 children in the AEC group. In the AEC group two fractures were secondarily reduced. In the BEC group one cast fell off two weeks after the trauma because of loose cast caused by subsided swelling. The AEC group had two cases of excoriation in the elbow crease, and two cases of transient neuropraxia of the superficial radial nerve. For both the number of complications and fracture displacement in the cast, there was no significant difference between the two groups.

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Table 4. Data on secondary outcomes.

	BEC	AEC
Days in cast	28.2 (± 5.1)	28.5 (± 5.7)
Days to first clinical examination	55.8 (± 21.6)	61.1 (± 21.2)
Days to final clinical examination	213.9 (± 36.2)	209.2 (± 40.9)
Limitation of wrist flexion-extension of the fractured arm (degrees)	1.9 (± 4.4)	1.0 (± 2.7)
Limitation of elbow flexion-extension of the fractured arm (degrees)	0 (± 2.5)	1.0 (± 3.7)
VAS comfort of cast *	8.4 (± 1.4)	5.6 (± 2.7)
VAS cosmetics fractured arm by parents	9.4 (± 0.9)	9.4 (± 1.0)
VAS cosmetics fractured arm by orthopedic surgeon	9.7 (± 0.6)	9.6 (± 0.7)
Total ABILHAND score at final clinical examination	40.7 (± 7.1)	41.8 (± 0.8)
Complications (number)	6	14

BEC: below-elbow cast. AEC: above-elbow cast; Values are presented as mean (± standard deviation). VAS: Visual Analogue Scale. * Significant difference between both groups ($p < 0.0001$). Other outcomes are not significantly different.

Using the selected grading system⁹, results in the BEC group were excellent in 48%, good in 46% and fair in 6%. In the AEC group the results were excellent in 58%, good in 32%, fair in 7% and poor in 3%. Similar results were found using the modified grading system (10). In the BEC group results were excellent in 77%, good in 14% and fair in 9%. In the AEC group results were excellent in 74%, good in 19% and fair in 7%. The results of both grading systems showed no significant difference between the two groups.

Table 5 shows significant differences in the groups in the amount of angulation between the radiographs made directly after trauma, and those made at cast removal and at final examination. In general, angulation increased in the period between trauma and removal of cast, while angulation decreased in the period between removal of cast and final examination. No other significant differences were found between the two groups.

Table 5. *Radiological outcomes.*

	BEC		
	Trauma	Removal of cast	Final clinical examination
AP ulna	6.5 (± 4.1) ²	5.5 (± 4.2)	3.3 (± 2.6) ²
AP radius	3.5 (± 2.8)	4.0 (± 3.8)	2.3 (± 2.7)
Lateral ulna	6.9 (± 4.8) ²	4.3 (± 3.3)	3.3 (± 2.6) ²
Lateral radius	9.0 (± 4.9) ¹²	11.4 (± 6.9) ¹	4.8 (± 3.4) ²
	AEC		
	Trauma	Removal of cast	Final clinical examination
PA ulna	6.7 (± 4.3) ²	6.6 (± 4.0)	4.4 (± 3.1) ²
PA radius	4.2 (± 3.3) ²	4.3 (± 4.2)	2.8 (± 2.6) ²
Lateral ulna	7.9 (± 5.4) ¹²	5.8 (± 4.7) ¹	4.0 (± 3.2) ²
Lateral radius	8.7 (± 5.0) ¹²	12.2 (± 5.8) ¹	6.3 (± 5.0)

²Radioulnar angulations (PA ulna, PA radius) and sagittal angulations (Lateral ulna, Lateral radius) presented in degrees as mean (\pm standard deviation).

No significant differences between BEC and AEC groups.

Significant differences (p-value < 0.05) were found between trauma radiographs and respectively radiographs removal of cast (¹) and radiographs final examination (²).

The interrater reproducibility of the radiological assessment showed an intraclass correlation of 0.81 and 0.89 for the radioulnar angulation of the ulna and radius, respectively. The intraclass correlation of the sagittal angulation was 0.92 for the ulna and 0.87 for the radius.

DISCUSSION

This randomised multicentre trial shows that BEC is as effective as AEC in the treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children. The children treated with BEC had similar limitation of pronation and supination, significantly higher cast comfort, needed significantly less help with dressing, and showed a tendency towards fewer complications.

Previous studies

In contrast with our results, an earlier study (6) found more limitation of pronation and supination in the AEC group than in the BEC group. Our mean limitation of pronation and supination was higher compared to these previous studies. This can be explained by our inclusion of patients with only both-bone fractures.

In a retrospective study of almost exclusively displaced both-bone forearm fractures treated with AEC after reduction, Daruwalla et al. found excellent results in 50%, good results in 33%, fair results in 17%, and no poor results⁹. Using the same grading system, our results seemed to be better, possibly caused by the absence of displaced fractures in our study group.

Using the modified grading system, in a selected group of malunited diaphyseal both-bone forearm fractures others reported 82% excellent results, 10% good results and 8% fair results¹⁰. These better results, despite the severity of malunited diaphyseal fractures, might be explained by the retrospective analysis and longer follow-up period.

We found twice as many fracture displacement in the group treated with AEC than in those treated with BEC. Similar findings have been reported by others^{5,6}. Immobilization of the elbow does not seem to prevent fracture displacement of a metaphyseal fracture of the distal forearm; this might be due to less moulding around the lower arm caused by the more difficult to apply AEC.

Radiographic assessment

Radiographic assessment showed that angulation increased in the period between trauma and removal of the cast, which might be explained by the secondary dislocation of the fracture during cast treatment. Decreased angulation in the period between removal of cast and final examination might be explained by remodelling by growth.

Limitations

This study has several limitations. Primarily, neither the children nor the independent orthopaedic surgeon were blinded during clinical follow-up, which might have influenced the clinical measurements. Obviously, blinding of the children was not possible because different types of cast were used. However, both the radiographic

assessors were blinded for the type of cast. The second limitation is our period of follow-up in this group of children with capacity for remodelling by growth. Although a follow-up of almost 7 months seems to be short, others found no change in clinical or radiographic status from 6 months after treatment to the final follow-up at an average of 2.8 years in children treated for displaced forearm fractures¹². Thereby Nilsson et al. described a persistent limitation during long term follow-up despite correction by growth and others advised an osteotomy to correct malunion as early as 6 months after trauma^{13,14}. Nevertheless, most children in our study regained a full range of pronation and supination after seven months.

Future research and study

Future studies could try to answer the following question: Why do fractures displace more in AEC than in BEC?

Conclusions

This randomised multicentre trial shows that there is similar limitation of pronation and supination after treatment of minimally displaced metaphyseal both-bone fractures of the distal forearm in children with either BEC or AEC. Children treated with BEC experienced significantly more cast comfort and significantly less interference with daily activities during the period of casting. To conclude, children with minimally displaced metaphyseal both-bone fractures of the distal forearm should be treated with a properly applied below-elbow cast.

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CHAPTER 3

Re-displacement of stable distal both-bone forearm fractures in children: *a randomised controlled multicentre trial*

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Colaris JW, Allema JH, Biter LU, de Vries MR, van de Ven CP, Bloem RM, Kerver AJ, Reijman M, Verhaar JA.

ABSTRACT

Introduction: Displaced metaphyseal both-bone fractures of the distal forearm are generally reduced and stabilised by an above-elbow cast (AEC) with or without additional pinning. The purpose of this study was to find out if re-displacement of a reduced stable metaphyseal both-bone fracture of the distal forearm in a child could be prevented by stabilisation with Kirschner wires.

Methods: Consecutive children aged < 16 years with a displaced metaphyseal both-bone fracture of the distal forearm (n=128) that was stable after reduction were randomised to AEC with or without percutaneous fixation with Kirschner wires. The primary outcome was re-displacement of the fracture.

Results: A total of 67 children were allocated to fracture reduction and AEC and 61 to reduction of the fracture, fixation with Kirschner wires and AEC. The follow-up rate was 96% with a mean follow-up of 7.1 months. Fractures treated with additional pinning showed less re-displacement (8% vs. 45%), less limitation of pronation and supination (mean limitation 6.9 (\pm 9.4) vs. 14.3 (\pm 13.6) degrees) but more complications (14 vs. 1).

Conclusions: Pinning of apparent stable both-bone fractures of the distal forearm in children might reduce fracture re-displacement. The frequently seen complications of pinning might be reduced by a proper surgical technique.

INTRODUCTION

Metaphyseal fractures of the distal forearm are common in childhood (1-3). Non-displaced fractures are generally treated with cast while displaced fractures need to be reduced and stabilised. After reduction, the method of stabilisation ranges from below-elbow cast only to percutaneous pinning with Kirschner wires (K wires) in combination with an above-elbow cast (AEC)⁴⁻¹⁴. Re-displacement of the fractures treated without percutaneous pinning has been described in 7-91% of patients^{6, 7, 11-13, 15-18} and such re-displacement can lead to malunion with reduced functional and cosmetic results^{19, 20}. In case of re-displacement the clinician is often confronted with a treatment dilemma, i.e. whether to accept some degree of re-displacement or to perform a secondary reduction of the fracture.

Several randomised studies compared treatment modalities for a combination of single-bone and both-bone forearm fractures in children. Two studies randomised between AEC and below-elbow cast and found the highest percentage of re-displacement in the AEC group, which could be explained by poor cast moulding^{4, 14}. Two other studies randomised between AEC with or without percutaneous pinning; re-displacement appeared only in the group without percutaneous pinning and was 21% in one and 39% in the other study^{9, 10}. Although these studies were well performed, none distinguished between fractures of the radius or ulna only, and fractures of both the radius and ulna, whereas the latter are notorious for their instability^{4, 18, 21}.

Therefore, we performed a multicentre study designed for only displaced metaphyseal both-bone fractures of the distal forearm in children, which were apparent stable after reduction in the operation room. After randomisation the fractures were treated with AEC alone or a combination of percutaneous pinning with AEC.

The purpose of this study was to find out if re-displacement of a reduced stable metaphyseal both-bone fracture of the distal forearm in a child could be prevented by stabilisation with K wires.

MATERIALS AND METHODS

Trial design and participants

This trial was part of a prospective multicentre study that followed several types of both-bone forearm fractures in children. For the present study consecutive children with a displaced metaphyseal fracture of the distal radius and ulna (Figure 1) were included after a visit at the emergency department of one of four participating Dutch hospitals: Erasmus Medical Center (Rotterdam), HAGA Hospital (The Hague), Reinier de Graaf Hospital (Delft) and Sint Franciscus Hospital (Rotterdam).



Figure 1. *Posteroanterior and lateral radiographs of a displaced distal both-bone forearm fracture which is stabilised by two Kirschner wires.*

The regional medical ethics committee approved the study, which was registered in ClinicalTrials.gov with registry identifier NCT00397852. Informed consent was obtained from all parents and from all children aged ≥ 12 years.

Only included were children aged < 16 years who sustained a displaced metaphyseal both-bone fracture of the distal forearm that was stable after closed reduction in the operating room. The criteria for reduction of the fracture were a

priori defined and based on previous studies (5, 6, 8, 22-28). A fracture was reduced if radius and/or ulna showed displacement on a posteroanterior and/or lateral radiograph. Displacement of the fracture was based on angulation (> 15 degrees for children aged less than 10 years old and >10 degrees for children between 10 and 16 years old) and/or translation (> half of the bone diameter) and/or any rotation of radius and/or ulna.

Exclusion criteria were fractures older than 1 week, severe open fractures (Gustilo II and III) (29), and re-fractures. The primary outcome was re-displacement of the fracture. Secondary outcomes were limitation of pronation and supination, limitation of flexion and extension of wrist and elbow, complication rate, complaints in daily life, radiological assessment and cosmetics of the fractured arm.

Procedures

A surgeon reduced the fracture in the operating room under general anaesthesia with fluoroscopic guidance. After optimal reduction by closed means, the fracture was tested for stability. A fracture was defined as unstable if full range of pronation and supination of the proximal forearm caused re-displacement of the fracture. This test for stability was used before in a group of children with forearm fractures[†]. Unstable fractures were excluded and treated with percutaneous pinning and AEC for 4 weeks. The remaining fractures were defined as stable and were randomised between AEC alone and percutaneous pinning with AEC, both for 4 weeks.

The surgeon performed the percutaneous pinning according to a standard technique¹⁰. A small skin incision was made over the radial styloid and blunt dissection of soft tissue was carried down to the bone. A K wire was directed proximally and ulnarly across the fracture site, engaging the opposite cortex. A second K wire was inserted from dorsal to volar across the fracture site through a small incision over the interval between the fourth and fifth dorsal compartments after blunt dissection down to the bone. Injury to the sensory branch of the radial nerve and the extensor tendons was avoided. The K wires were bent, cut and left transcutaneous. Additionally, the surgeon applied an AEC in the operation room. Primarily a stockinet and layer of wool were applied to protect the skin, bony prominences and K wires. Secondarily a well-fitted plaster slab was applied which covered approximately 2/3 of the circumference of the arm. Finally, a bandage was

wrapped around the arm. The elbow was set in 90 degrees of flexion and the wrist in neutral position. All children received a sling for at least 1 week.

The children underwent clinical and radiological evaluation at 1, 2 and 4 weeks after initial trauma. During these visits, a cast technician revised and renewed the casts where necessary. Re-displacement of the fracture was defined by the loss of reduction (angulation and/or translation) according to the primary reduction criteria. These re-displaced fractures required a second reduction with percutaneous pinning in the operating room. Finally, both the cast and the K wires were removed in the outpatient clinic after 4 weeks.

One orthopaedic surgeon (who was not involved in treatment and was not blinded) examined all children at 2 and 6 months after initial trauma. Flexion and extension of wrist and elbow in combination with pronation and supination of both arms were evaluated by a standardised procedure (Table 2)³¹.

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 degrees of limitation (Table 3)²³. Children with at least 30 degrees of functional impairment at 2 months examination received a referral for physiotherapy.

At the 6-month examination, parents and the orthopaedic surgeon completed a visual analogue scale (VAS) cosmetics, with maximum score for similar appearance of the fractured and non-fractures arm, to evaluate forearm alignment and scars. During the same examination, the parents filled in the ABILHAND-Kids questionnaire, that is a measure of manual ability for children with upper limb impairments (Table 2). The scale is validated for cerebral palsy children and measures a child's ability to manage daily activities that require the use of the upper limbs, with a maximum score of 42³².

Antero-posterior and lateral radiographs were taken at scheduled times (Table 4). The first radiographs were made in the emergency room followed by radiographs after reduction and during follow-up at 1, 2 and 4 weeks. The final radiographs were made at 6 months after the trauma. Angulation, translation, shortening and rotation of fractures of all available radiographs were measured by the orthopaedic surgeon to determine primary displacement, displacement during the first 4 weeks, and final displacement at 6 months. The presence of rotation was evaluated by differences in width of ulna and radius on lateral and posteroanterior radiographs (33).

Randomisation and masking

An independent physician randomised the children by sealed envelopes with varied block sizes. The children, parents and clinicians were not blinded for randomisation.

Statistical methods

To assess the number of children required for this trial, a superiority test was used to demonstrate a difference in re-displacement of 17% between both groups: 3% re-displacement in the group treated with percutaneous pinning with AEC, and 20% re-displacement in the group treated with AEC alone^{6,8,9,11,13,16,17,24,34-39}. With an *a priori* calculation it was determined that, with a power of 80% and a significance of 0.05, the two groups should consist of ± 55 children each.

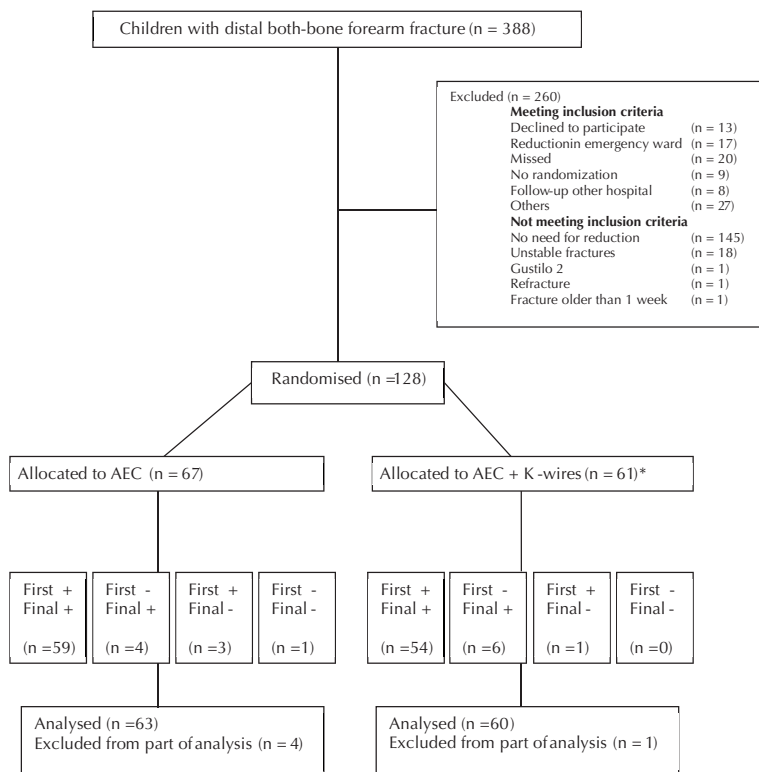
First, it was established whether the variables had a normal distribution using the normality Shapiro-Wilk test. Based on these analyses, the results are presented as means (standard deviations (SD)). The primary research question was analysed using logistic regression analysis (re-displacement as dependent variable, and intervention as independent variable). If necessary, adjustments for unbalanced covariates took place. Differences between both groups (percutaneous pinning with AEC vs. AEC alone) for the secondary outcome measures were analysed by one-way Anova to correct for multiple comparisons (Bonferroni). Statistical analyses were performed with SPSS 17.0 (SPSS Inc., Chicago, USA).

To assess the interrater reproducibility an independent trauma surgeon re-measured the angulation of the fracture of 45 children.

RESULTS

Between January 2006 and August 2010 a total of 388 children with a metaphyseal both-bone fracture of the distal forearm were treated in the four Dutch hospitals. After exclusion for several reasons (details are given in Figure 2), 128 children were included of which 67 were allocated to AEC and 61 to K wires with AEC.

Figure 2. Flow diagram of enrollment



n = number of children; AEC = above elbow cast; First: first examination;

Final: final examination; + : examined; - : not examined; *insertion of K-wires failed in one child.

The follow-up rate was 96% with a mean follow-up of 7.1 months. Table 1 shows the baseline characteristics of the total study population according to the randomisation group.

Table 1. *Baseline characteristics*

	Total	AEC	K-wires + AEC
Number of children	128	67	61
Age at time of fracture, years (mean ± SD)	8.8 (± 3.1)	8.7 (± 3.2)	9.0 (± 3.0)
Gender, % male	64.8	62.7	67.2
Dominant arm fractured, %	45.7	47.0	44.3
Type fracture radius, %			
Torus	0	0	0
Greenstick	22.2	23.4	20.0
Complete	77.8	76.6	80.0
Type fracture ulna, %			
Torus	7.1	7.6	6.7
Greenstick	46.9	43.9	50.0
Complete	46.0	48.5	43.3

AEC: Above Elbow Cast; K-wires: Kirschner wires; SD = standard deviation.

There are no significant differences between the groups.

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In the AEC group 30 fractures showed re-displacement of which 17 were reduced a second time. In the group with additional K wires, five fractures showed re-displacement of which one fracture was reduced a second time (Table 2).

Table 2. *Outcomes.*

	AEC n =67	K-wires + AEC n = 61
Re-displacement, % *	44.8	8.2
Days in cast	33.4 (±8.8)	32.2 (±6.1)
Days untill first clinical examination	68.4 (±25.4)	69.7 (±28.5)
Days untill final clinical examination	216.3 (±49.1)	215.5 (±47.2)
Referral to physiotherapy, %	54.5	35.6
Number of visits to physiotherapy	3.9 (±7.3)	2.6 (±6.1)
Limitation of wrist flexion-extension of the fractured arm, degrees	4.4 (±6.2)	3.8 (±7.4)
Limitation of elbow flexion-extension of the fractured arm, degrees	0.5 (±2.0)	0.2 (±2.1)
VAS cosmetics fractured arm by parents	8.5 (±1.8)	8.0 (±2.2)
VAS cosmetics fractured arm by orthopedic surgeon	8.9 (±1.2)	8.4 (±1.3)
Total ABILHAND score at final clinical examination	41.5 (±1.6)	41.9 (±0.4)

Values are presented as mean (± standard deviation) unless stated otherwise. AEC: above elbow cast; K-wires: Kirschner wires; VAS: Visual Analogue Scale.

* Significant difference ($p < 0.0001$).

Re-displacement in the group with additional K wires was caused by suboptimal position of the K wires in 2 children and re-displacement of the ulna in 3 children. Fracture re-displacement was first observed in 14 children at the 1-week examination, in 19 children at the 2-week examination and in 2 children at the 4-week examination. Thereby, we found a similar rate of re-displacement in greenstick and complete fractures.

Pronation and supination at the final examination showed significantly less limitation in the group initially treated with additional K wires (Table 3).

Table 3. *Limitation of pronation and supination of fractured arm.*

	AEC n =67	K-wires + AEC n = 61
Two months after the fracture		
none	9.7	11.0
1-10 degrees	22.6	34.5
11-20 degrees	14.5	18.2
21-30 degrees	14.5	14.5
>31 degrees	38.7	21.8
Mean limitation (+SD), degrees	27.2 (± 21.9)	21.9 (± 21.4)
Six months after the fracture		
none	23.8	48.3
1-10 degrees	31.7	31.7
11-20 degrees	19.0	10.0
21-30 degrees	14.3	8.3
>31 degrees	11.2	1.7
Mean limitation (+SD), degrees	14.3 (± 13.6)*	6.9 (± 9.4)*

AEC: Above Elbow Cast; K-wires: Kirschner wires. Data are presented as percentage.

SD = standard deviation.

* Significant difference (p = 0.001)

Thereby, more complications occurred in the group treated with K wires and AEC than in the group treated with AEC (14 vs 1). The complications seen in the group treated with K wires and AEC were 7 subcutaneous K wires, 3 re-fractures, 2 superficial infections, 1 failed insertion of K wires and 1 transient neuropraxia. This last complication occurred also once in the group treated with only AEC.

Other secondary outcomes were similar in both groups and are shown in Table 2.

Measurement of the radiographs (Table 4) revealed a decrease in angulation and translation after reduction in both groups and an increase in angulation in the period between reduction and removal of the cast only in the group treated with

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AEC alone. Furthermore, a decrease in angulation in the period between the removal of the cast and the final examination was seen in both groups.

Table 4. Radiological outcomes.

	AEC				AEC + K-wires			
	Trauma	After reduction	Removal of cast	Final	Trauma	After reduction	Removal of cast	Final
Angulation								
AP ulna	13 (± 12) ²	5 (± 4) ^{2 3}	6 (± 4) ⁴	4 (± 3) ^{3 4}	14 (± 11) ²	5 (± 4) ²	5 (± 4)	4 (± 3)
AP radius	12 (± 9) ²	5 (± 4) ^{2 3}	8 (± 7) ^{1 3 4}	5 (± 4) ^{1 4}	15 (± 12) ²	4 (± 3) ^{2 3}	4 (± 2) ^{1 4}	3 (± 2) ^{1 3 4}
Lateral ulna	21 (± 17) ²	5 (± 4) ^{2 3}	6 (± 5) ⁴	3 (± 3) ^{3 4}	19 (± 15) ²	5 (± 5) ^{2 3}	5 (± 4) ⁴	4 (± 3) ^{3 4}
Lateral radius	21 (± 12) ²	7 (± 5) ^{1 2 3}	13 (± 11) ^{1 3 4}	8 (± 5) ^{1 4}	22 (± 11) ²	5 (± 4) ^{1 2}	6 (± 5) ^{1 3}	4 (± 2) ^{1 3}
Translation								
PA ulna	12 (± 24) ²	4 (± 11) ²	*	*	9 (± 25)	6 (± 14)	*	*
PA radius	24 (± 28) ²	7 (± 9) ²	*	*	29 (± 36) ²	6 (± 9) ²	*	*
Lateral ulna	19 (± 31) ²	5 (± 13) ²	*	*	10 (± 24) ²	4 (± 9) ²	*	*
Lateral radius	54 (± 47) ²	8 (± 13) ²	*	*	63 (± 45) ²	5 (± 9) ²	*	*
Shortening of radius and/or ulna								
%	68.2				67.8			
Rotation of radius and/or ulna								
%	15.2				21.7			
Angulation: Radioulnar angulation (PA ulna, PA radius) and sagittal angulation (Lateral ulna, Lateral radius) presented in degrees as mean (\pm standard deviation).								
Translation: Radioulnar translation (PA ulna, PA radius) and sagittal translation (Lateral ulna, Lateral radius) presented in percentage of the width of ulna or radius as mean (\pm standard deviation).								
Shortening and rotation as percentage of appearance.								
¹ Significant differences between both groups.								
^{2 3 4} Significant differences within one group								

The interrater reproducibility of the radiological assessment by measurement of angulation of the ulna and radius on both the posteroanterior and lateral radiographs showed an intraclass correlation (ICC) range of 0.81-0.92.

DISCUSSION

The purpose of this study was to find out if re-displacement of a reduced stable metaphyseal both-bone fracture of the distal forearm in a child could be prevented by stabilisation with K wires. As expected, this study shows that additional percutaneous pinning decreased fracture re-displacement compared to AEC alone. It was also found that children treated with additional pinning showed a small but significant decrease of limitation of pronation and supination after 7 months. Nevertheless, the group treated with additional pinning paid the price with a higher rate of complications. Most of these complications consisted of subcutaneous K wires that could probably have been avoided by not cutting the transcutaneous K wires too short.

Previous studies

Previous randomised trials reported re-displacement after reduction of distal metaphyseal forearm fractures in children treated with an AEC in 15-42%^{4,9,10,14} while retrospective studies found 7-91%^{6,7,11-13,15-18}. Our re-displacement rate of 45% in the group treated with AEC alone is relatively high and could be explained by more instable both-bone forearm fractures and the application of a plaster slab instead of a circumferential cast directly after reduction.

Our group of children treated with K wires showed more re-displacement than reported previously^{5,6,10,12}. This re-displacement was caused by technical errors in 2 children and re-displacement of the non-fixated ulna in 3 children.

Similar to other studies^{9,11} only 51% of our re-displaced fractures were reduced a second time, although this was suggested in our study protocol. Although not planned, this illustrates the reluctance of the treating surgeons to choose for a second reduction (for various reasons). On the one hand the treating surgeon may hope or expect correction of the malunion due to growth, on the other hand the surgeon may be reluctant to burden the child again or finds it difficult to accept failure of the initial treatment.

Additional operations after the first reduction were mainly caused by a second reduction and removal of subcutaneous K wires. In contrast with an earlier study⁹, in the present study the K wires were generally removed in the outpatient clinic without problems, which substantially decreases the number of re-operations.

The limitation of pronation and supination in the children treated with AEC alone was higher in the present study than in earlier reports^{5,8-10,13,23,40}. Our less favourable outcomes might be explained by the inclusion of only children with both-bone forearm fractures, the prospective nature of our study, the high rate and relatively short time of follow-up. On closer examination, we found a limitation of pronation and supination of ≥ 30 degrees in 11 children treated with AEC and in 3 children treated with K wires and AEC. Only 6 of these children showed a malunion at final radiographs. These findings support the opinion that malunion is not the only cause of limitation of pronation and supination after both-bone forearm fractures in children^{27,41-45}.

Radiological assessment

As expected, measurement of the radiographs revealed a decrease in angulation and translation after reduction in both groups, which is explained by a correct reduction. The increase in angulation in the period between reduction and removal of the cast only in the group treated with AEC alone was caused by re-displacement. In both groups, a decrease in angulation in the period between the removal of the cast and the final examination was caused by correction due to growth.

Study limitations

The first limitation was the wide age range of the included children combined with our strict reduction criteria. This study was part of a prospective multicentre randomised study that followed all types of both-bone forearm fractures in children and used the same reduction criteria for metaphyseal and diaphyseal forearm fractures. Although we adjusted the criteria for reduction to two age groups, the reduction criteria for metaphyseal fractures in the youngest children may have been too strict.

The second limitation was our relatively short time of follow-up. A longer period of follow-up might reduce the number of children with an impairment of function as is described by Price et al.⁴⁰.

To conclude, this is the first randomised multicentre study to evaluate displaced metaphyseal both-bone fractures of the distal forearm in children. Pinning of apparent stable both-bone fractures of the distal forearm in children might reduce

fracture re-displacement and might result in less limitation of pronation and supination. The frequently seen complications of pinning might be reduced by a proper surgical technique.

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PART III

DIAPHYSEAL BOTH-BONE FOREARM FRACTURES

CHAPTER 4

Early conversion to below-elbow cast for non-reduced diaphyseal both-bone forearm fractures in children is safe: preliminary results of a multicentre randomised controlled trial

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ABSTRACT

Introduction: This multicentre randomised controlled trial was designed to explore whether 6 weeks above-elbow cast (AEC) or 3 weeks AEC followed by 3 weeks below-elbow cast (BEC) cause similar limitation of pronation and supination in non-reduced diaphyseal both-bone forearm fractures in children.

Materials and Methods: Children were randomly allocated to 6 weeks AEC or to 3 weeks AEC followed by 3 weeks BEC. The primary outcome was limitation of pronation and supination after 6 months. The secondary outcomes were re-displacement of the fracture, complication rate, limitation of flexion and extension of wrist and elbow, cast comfort, cosmetics, complaints in daily life and assessment of radiographs.

Results: A group of 23 children was treated with 6 weeks AEC and 24 children with 3 weeks AEC and 3 weeks BEC. The follow-up rate was 98% with a mean follow-up of 7.0 months.

The mean limitation of pronation and supination was 23.3 (\pm 22.0) for children treated with AEC and 18.0 (\pm 16.9) for children treated with AEC and BEC. The other study outcomes were similar in both groups.

Conclusions: Early conversion to BEC is safe in the treatment of non-reduced diaphyseal both-bone forearm fractures in children.

INTRODUCTION

Both-bone diaphyseal forearm fractures are common in children and are generally treated with cast, intramedullary nails or plates. The treatment with cast usually consists of an above-elbow cast (AEC) for 6-9 weeks, although conversion to a below-elbow cast (BEC) at the end of treatment is frequently seen¹⁻¹¹. Although many of these fractures heal without complications, limitation of pronation and supination can occur. An average limitation of 20 degrees in about 15% of children has been reported^{6,12,13}.

This limitation of pronation and supination after both-bone diaphyseal forearm fractures in children seems to be caused by both malunion of the radius and/or the ulna, and a contracture of the surrounding soft tissue¹³⁻¹⁸.

Early conversion to BEC in the treatment of these fractures could potentially effect the limitation of pronation and supination in two opposing ways. On the one hand, BEC does not immobilise the elbow and could therefore result in displacement of the fracture, malunion and consequently more limitation. On the other hand, BEC allows free movement of the elbow that could result in less contractures of soft tissue and consequently less limitation.

Nevertheless, the influence of AEC and BEC on limitation of pronation and supination remains unclear. Therefore, this multicentre randomised controlled trial aimed to clarify the role of AEC and BEC on limitation of pronation and supination in non-reduced both-bone diaphyseal forearm fractures in children. Specifically, the following question was explored: do 6 weeks AEC as compared with 3 weeks AEC followed by 3 weeks BEC cause similar limitation of pronation and supination?

MATERIALS AND METHODS

Trial design and participants

A multicentre randomised controlled trial was performed that included consecutive children with a diaphyseal forearm fracture of the radius and ulna who visited the emergency department of one of four participating hospitals. The Dutch hospitals participating in this study were Erasmus Medical Center (Rotterdam), HAGA Hospital (The Hague), Reinier de Graaf Hospital (Delft) and Sint Franciscus Hospital

(Rotterdam). The regional medical ethics committee approved the study and it was registered in ClinicalTrials.gov with registry identifier NCT00314600. Informed consent was obtained for participation from all parents and from all children aged ≥ 12 years.

We included children with an age < 16 years who sustained a diaphyseal both-bone forearm fracture without need for reduction (Figure 1).



Figure 1. Radiographs of a minimally displaced diaphyseal both-bone forearm fracture

The criteria for reduction were *a priori* defined and based on earlier studies (3, 15, 19-26) (Table 1). Exclusion criteria were fractures older than 1 week, severe open fractures (Gustilo II and III) (27) and re-fractures.

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

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

Because most published studies do not adequately address true, final range of pronation and supination²⁸ we choose limitation of pronation and supination compared to the non-injured site 6 months after the initial trauma as primary outcome. The secondary outcomes were re-displacement of the fracture, complication rate, limitation of flexion and extension of wrist and elbow, cast comfort, cosmetics, complaints in daily life, and assessment of radiographs. The children were allocated to either 6 weeks of AEC or to 3 weeks of AEC followed by 3 weeks of BEC.

Procedures

Trained nurses applied the AEC in the plaster room of the emergency department. First, a stockinet and layer of wool were applied to protect the skin and bony prominences. Then, a well-fitted plaster slab was applied which covered about 2/3 of the circumference of the arm. Finally, a bandage was wrapped around the arm. The elbow was set in 90 degrees of flexion and the forearm in neutral position. All children received a sling for at least 1 week. The children visited a surgeon at 1, 3 and 6 weeks after the initial trauma. A cast technician revised and renewed the casts where necessary. In children allocated to BEC, the cast technician applied a circumferential BEC after 3 weeks; this BEC allowed free movement of the elbow joint.

Fracture displacement, as defined by the loss of reduction according to the primary reduction criteria (Table 1), required new fracture reduction. Finally, the cast was removed 6 weeks after initial treatment.

One orthopaedic surgeon (not involved in the primary treatment) examined all children 2 and 6 months after the initial trauma. Flexion and extension of wrist and elbow in combination with pronation and supination of both arms were evaluated using a standardised procedure²⁹. 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 degrees of limitation³.

Children with at least 30 degree of functional impairment at the 2-month examination were referred to physiotherapy. Furthermore, the parents filled in a visual analogue scale (VAS) to evaluate the comfort of the cast, with the highest score for maximal comfort. In addition, the parents were asked to fill in a questionnaire to evaluate difficulties with seven activities of daily living during the period of cast. This questionnaire has previously been used in a similar group of children³⁰.

The parents and the orthopaedic surgeon completed a VAS cosmetics of the fractured arm, with a maximum score for similar appearance of the fractured and non-fractured arm. In the same consultation, complaints of the fractured arm were documented using a modified grading system. This grading system combines limitation of pronation and supination with complaints in daily life or during strenuous activities. It has previously been used in a similar group of children³¹. The parents also filled in an ABILHAND-Kids questionnaire³², which is a measure of manual ability for children with upper limb impairments. This scale has been validated for children with cerebral palsy and measures a child's ability to manage daily activities that require use of the upper limbs, with a maximum score of 42³².

Radiographs were taken in the emergency room followed by radiographs during follow-up at 1, 3 and 6 weeks. The final radiographs were made 6 months after the initial trauma. The orthopaedic surgeon measured angulation, translation, rotation and shortening of fractures to determine primary displacement, displacement during treatment with cast and final displacement at 6 months. The presence of rotation was evaluated by differences in the width of the ulna and radius on lateral and posteroanterior radiographs³³.

Randomisation and masking

An independent physician randomised the children by sealed envelopes with varied block sizes. None of the children, parents, surgeon, cast technician and independent orthopaedic surgeon was blinded for allocation.

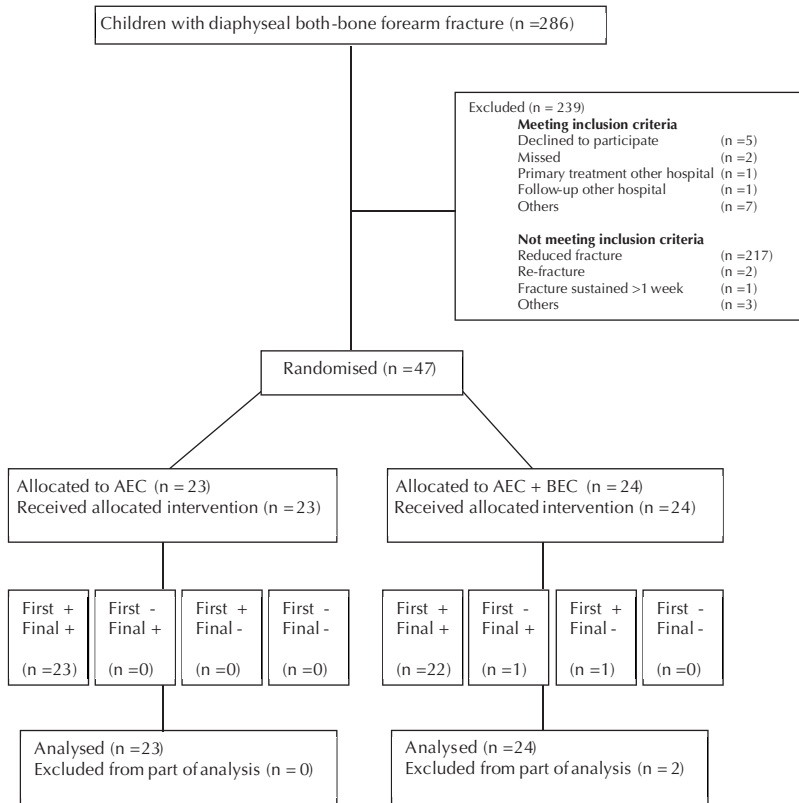
Statistical methods

The primary aim of the study was to determine whether 6 weeks AEC compared with 3 weeks AEC and 3 weeks BEC, cause equal limitation of pronation and supination 6 months after the initial trauma. The required number of children for this equivalence study was calculated *a priori*. Equivalence between the two groups was defined as a maximum of 15 degrees less pronation or supination in the group treated with AEC and BEC. We chose 15 degrees of limitation in order to stay within the safe margins of good results as graded previously³. With an *a priori* calculation it was determined that with a power of 80%, an alpha of 0.05 and a standard deviation (SD) of 15 degrees, the two groups should consist of ± 30 children each.

First, 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 and SD. The primary research question was analysed using linear regression analysis (limitation of pronation and supination of the fractured arm 6 months after initial trauma as dependent variable, and the intervention as independent variable). If necessary, adjustments for unbalanced covariates were made. Differences between the two groups for the secondary outcome measures were analysed by one-way Anova to correct for multiple comparisons (Bonferroni). Statistical analyses were performed with SPSS 17.0 (SPSS Inc., Chicago, USA).

RESULTS

Between January 2006 and August 2010 a total of 47 children were included in the four Dutch hospitals. A group of 23 children was randomised to 6 weeks AEC and 24 children were randomised to 3 weeks AEC followed by 3 weeks BEC (Figure 2).



n = number of children; AEC = above elbow cast; BEC = below elbow cast; First: first examination; Final: final examination; + : examined; - : not examined.

Figure 2. Flowchart of enrolment in the study.

Table 2 shows the baseline characteristics of the total study population and per randomisation.

Table 2. *Baseline characteristics of the study population.*

	Total	AEC	AEC + BEC
Number of children	47	23	24
Age in years at time of fracture: mean (SD)	6.4 (\pm 3.4)	6.5 (\pm 3.5)	6.2 (\pm 3.4)
Gender, % male	48.9	56.5	41.7
Dominant arm fractured, %	41.3	40.9	41.7
Type fracture radius, %			
Greenstick	68.1	73.9	62.5
Complete	31.9	26.1	37.5
Location of fracture of radius*, %	57.1	60.3	52.7
Type fracture ulna, %			
Greenstick	61.7	56.5	66.7
Complete	38.3	43.5	33.3
Location of fracture of ulna*, %	42.6	41.7	42.6

AEC: above-elbow cast; BEC: below-elbow cast; SD = standard deviation; *

The location of the fracture was calculated by dividing the distance of the fracture to the wrist by the length of the bone; Values are presented as median; There are no significant differences between the two groups.

Our follow-up rate was 98% at a mean of 213.2 (\pm 45.4) days for children treated with AEC, and 214.0 (\pm 44.0) days for children treated with AEC and BEC.

Table 3 shows that there were no significant differences in limitation of pronation and supination at 2 and 6 months follow-up. The mean limitation of pronation and supination at 6 months follow-up was 23.3 (\pm 22.0) for children treated with AEC and 18.0 (\pm 16.9) for children treated with AEC and BEC.

Table 3. *Limitation of pronation and supination of the fractured arm.*

	AEC	AEC + BEC
Two months after fracture		
None	6.8	13.1
1-10 degrees	20.3	31.1
11-20 degrees	25.4	19.7
21-30 degrees	15.3	8.2
>31 degrees	32.2	27.9
Mean limitation/SD (degrees)	27.9 (\pm 22.1)	20.8 (\pm 17.9)
Six months after fracture		
None	21.3	32.8
1-10 degrees	19.7	28.1
11-20 degrees	29.5	21.9
21-30 degrees	11.5	10.9
>31 degrees	18.0	6.3
Mean limitation/SD (degrees)	17.8 (\pm 16.1)	11.3 (\pm 11.5)
AEC: Above-elbow cast; BEC: Below-elbow cast; Data are presented as percentage; SD = standard deviation;		
No significant differences after correction for baseline imbalanced variables, namely age, dominant arm and type of fracture radius.		

Using the grading system for limitation of pronation and supination³, the results of children treated with AEC were excellent in 26%, good in 26%, fair in 17% and poor in 31%. For the children treated with AEC and BEC these results were excellent in 26%, good in 26%, fair in 31% and poor in 17%. Similar results were found using the modified grading system³¹. In the AEC group results were excellent in 43%, good in 22% and fair in 35%. In the group treated with AEC and BEC results were excellent in 39%, good in 44% and fair in 17%.

The secondary outcome measures are reported in Table 4 and show similar results for both groups. No significant difference was found between the groups on the questionnaire used to evaluate difficulties with the 7 daily activities during the period of cast³⁰.

Table 4. *Data on secondary outcomes.*

	AEC	AEC + BEC
VAS comfort	6.2 (± 1.6)	8.0 (± 1.9)
VAS cosmetics fractured arm by parents	8.1 (± 2.6)	7.4 (± 2.6)
VAS cosmetics fractured arm by orthopaedic surgeon	8.1 (± 1.9)	7.9 (± 2.2)
Total ABILHAND score at final clinical examination	41.6 (± 1.1)	41.7 (± 1.1)
Days in cast	42.6 (± 3.6)	43.3 (± 7.9)
Days until first clinical examination	74.7 (± 28.9)	79.7 (± 25.8)
Days until final clinical examination	213.2 (± 45.4)	214.0 (± 44.0)
Referral to physiotherapy, %	43.5	47.8
Number of visits to physiotherapy	3.2 (± 5.7)	3.7 (± 6.1)
Limitation of wrist flexion-extension of the fractured arm, degrees	2.4 (± 5.4)	1.7 (± 3.6)
Limitation of elbow flexion-extension of the fractured arm, degrees	0.4 (± 2.1)	1.1 (± 3.0)

AEC: above-elbow cast; BEC: below-elbow cast; VAS: visual analogue scale; Values are presented as mean (± standard deviation) unless stated otherwise; There are no significant differences between the two groups.

There were 9 complications in the group treated with AEC and 8 complications in the group treated with AEC and BEC (Table 5). Fracture displacement was seen in 11 children, 10 of whom had AEC during the displacement. Fracture displacement was observed in 3 children at the 1-week examination, in 5 children at the 3-week examination and in 3 children at the 6-week examination. Two of these displaced fractures were reduced and one was stabilised with intramedullary nails. Similar rates of displacement were found for greenstick and complete fractures.

Table 5. *Data on complications.*

	AEC	AEC + BEC
Displacement during cast	5	6
Re-fracture	2	2
Transient neuropraxia	1	-
Wound dehiscence after intramedullary nails	1	-
Total complications	9	8

AEC = above-elbow cast; BEC = below-elbow cast; Values are presented as number of complications; No significant difference was found between the two groups.

Chapter 4

Radiographs made directly after trauma and at final examination show that fracture angulation decreased over time (Table 6). Translation was calculated only at the start of treatment because formation of callus disturbed measurements in the later periods. Rotation and shortening of fractures were only seen on radiographs made directly after trauma.

Table 6. Data on radiological outcomes.

	AEC			AEC + BEC		
	Trauma	Removal of cast	Final	Trauma	Removal of cast	Final
Angulation						
PA ulna	6 (\pm 3)	5 (\pm 4)	5 (\pm 4)	8 (\pm 7)	6 (\pm 5)	5 (\pm 4)
PA radius	7 (\pm 4)	5 (\pm 4)	4 (\pm 4)	8 (\pm 6)	8 (\pm 6)	7 (\pm 6)
Lateral ulna	11 (\pm 6) ¹	5 (\pm 4)	4 (\pm 4) ¹	(\pm 12)	7 (\pm 5)	7 (\pm 5)
Lateral radius	11 (\pm 5)	11 (\pm 5) ¹	9 (\pm 4) ¹	15 (\pm 11)	13 (\pm 7) ¹	11 (\pm 6) ¹
Translation						
PA ulna	3 (\pm 6)	*	*	1 (\pm 3)	*	*
PA radius	7 (\pm 22)	*	*	4 (\pm 9)	*	*
Lateral ulna	3 (\pm 8)	*	*	5 (\pm 15)	*	*
Lateral radius	4 (\pm 14)	*	*	1 (\pm 3)	*	*
Shortening of radius and/or ulna						
%	4.3			0		
Rotation of radius and/or ulna						
%	4.3			0		

Angulation: Radioulnar angulation (PA ulna, PA radius) and sagittal angulation (Lateral ulna, Lateral radius) presented in degrees as mean (\pm standard deviation).

Translation: Radioulnar translation (PA ulna, PA radius) and sagittal translation (Lateral ulna, Lateral radius) presented in percentage of the width of ulna or radius as mean (\pm standard deviation).

Shortening and rotation as percentage of appearance.

*Translation not relevant because of formation of callus.

¹ Significant difference within one group.

No significant difference between AEC and AEC + BEC group.

None of the included fractures was primarily reduced, although 19 fractures should have been directly reduced according to the reduction criteria. Five of these fractures were reduced during the treatment with cast, and one of these fractures was stabilised with intramedullary nails. We found a malunion on final radiographs in 4 children treated with AEC with, respectively, 0, 35, 50 and 75 degrees of limitation of pronation and supination. Seven children treated with AEC and BEC suffered from a malunion with, respectively, 0, 10, 10, 20, 25, 40 and 55 degrees of limitation.

DISCUSSION

This randomised controlled trial evaluated the influence of early conversion from AEC to BEC in the treatment of non-reduced diaphyseal both-bone forearm fractures in children. No significant difference was found on several clinical and radiographic outcomes. At 6 months follow-up, both groups showed a similar but high limitation of pronation and supination. Thereby, early conversion did not result in more re-displacement of the fracture.

A limitation of pronation and supination of > 30 degrees at final follow-up was found in 8 children treated with AEC (3 complete fractures and 5 greenstick fractures) and in 4 children treated with AEC and BEC (3 complete fractures and 1 greenstick fractures). Malunions were seen in 3 of these 8 children treated with AEC and in 2 of these 4 children treated with AEC and BEC. Consequently, malunion does not seem to be the only cause of limitation of pronation and supination in this group of children. Furthermore, the higher incidence of limitation in the group treated with only AEC suggests a possible role of immobilisation of the elbow. In contrast with BEC, AEC makes movement of the elbow impossible which can result in limitation of pronation and supination due to contracture of the joint capsules, periarticular soft tissues and the interosseous membrane. The absence of limitation of flexion and extension of elbow and wrist makes a contracture of joint capsules and periarticular soft tissue less plausible. Therefore, limitation of pronation and supination may be caused by a malunion and/or contracture of the interosseous membrane, as also indicated by others^{14,15,17,18,34,35}.

Although restoration of forearm rotation is essential in evaluating the success of forearm fracture management in children, most studies do not adequately address

true, final range of pronation and supination²⁸. Compared with earlier studies, in the present study limitation of pronation and supination was relatively high. Using the grading system (3) we found excellent results in 26% of both groups, whereas others reported excellent results in 44%³, 77%³¹, 83%³⁶, 89%⁶ and 100%^{2,22,37}. Our less favourable results may be caused by our prospective study design with its high rate of follow-up, detailed measurements, and our high percentage of malunions.

Previous studies reported fracture displacement in conservatively treated forearm fractures in 7-27% of their patients^{2,6,22,38-41}, whereas we found 23%. The fracture displacement occurred in 91% during treatment with AEC and in 73% of them during the first 3 weeks. Therefore, even minimally displaced diaphyseal both-bone forearm fractures in children have a tendency to displace, and this is not prevented by immobilisation of the elbow in an AEC.

Study Limitations

This study had several limitations. First, the number of children did not reach the estimated ± 30 required in each group. The force of the trauma needed to fracture the diaphysis of both the radius and ulna seemed more often to cause a fracture that needed reduction. This corresponds with our finding that only 24% of diaphyseal both-bone forearm fractures in the present study were non-reduced fractures. A previously scheduled time frame made further inclusion of patients impossible. Therefore, because this study was statistically underpowered, the results should be interpreted with caution.

Second, not all fractures were reduced according to our *a priori* defined criteria. Possible explanations for this could be errors in the measurement of displacement, or expectation of correction by growth. Nevertheless only non-reduced fractures were included.

Conclusion

Early conversion to BEC is safe in the treatment of children with non-reduced diaphyseal both-bone forearm fractures and does not seem to influence forearm rotation. Displacement of the fracture is often seen which requires vigilance, especially during the first 3 weeks of treatment.

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CHAPTER 5

Conversion to below-elbow cast after 3 weeks is safe for diaphyseal both-bone forearm fractures in children: a multicentre randomized controlled trial involving 127 children

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ABSTRACT

Background: It is unclear whether it is safe to convert above- elbow cast (AEC) to below-elbow cast (BEC) in a child who has sustained a displaced diaphyseal both-bone forearm fracture that is stable after reduction. In this multicentre study, we wanted to answer the question: does early conversion to BEC cause similar forearm rotation to that after treatment with AEC alone?

Children and methods: Children were randomly allocated to 6 weeks of AEC, or 3 weeks of AEC followed by 3 weeks of BEC. The primary outcome was limitation of pronation/supination after 6 months. The secondary outcomes were re-displacement of the fracture, limitation of flexion/extension of the wrist and elbow, complication rate, cast comfort, complaints in daily life, and cosmetics of the fractured arm.

Results: 62 children were treated with 6 weeks of AEC, and 65 children were treated with 3 weeks of AEC plus 3 weeks of BEC. The follow-up rate was 60/62 and 64/65, respectively with a mean time of 6.9 (4.7–13) months. The limitation of pronation/supination was similar in both groups (18 degrees for the AEC group and 11 degrees for the AEC/BEC group). The secondary outcomes were similar in both groups, with the exception of cast comfort, which was in favour of the AEC/BEC group.

Interpretation: Early conversion to BEC is safe and results in greater cast comfort.

INTRODUCTION

Most displaced diaphyseal both-bone forearm fractures in children can be treated successfully with closed reduction and above-elbow cast (AEC) for 6–9 weeks, but AEC is often converted to below-elbow cast (BEC) in the last weeks of treatment. Although most of these fractures heal uneventfully, limitation of pronation and supination can give disappointing results. Previous studies have found an average limitation of 20 degrees in about 15% of children. The cause of this limitation is unknown, but malunion and contracture of soft tissues have been suggested in some studies¹⁻⁹. Early conversion to BEC in the treatment of these fractures could potentially affect limitation of pronation and supination in 2 opposing ways. On the one hand, early conversion to BEC could result in fracture displacement, leading to malunion and resulting in limitation of pronation and supination. On the other hand, AEC may lead to a limitation of pronation and supination because of contracture of soft tissue by immobilisation of the elbow. We therefore set up a randomized controlled multicentre trial to answer the following question: does early conversion from AEC to BEC cause forearm rotation that is similar to that from AEC alone in reduced stable diaphyseal both-bone forearm fractures in children?

CHILDREN AND METHODS

Trial design and participants

We performed a multicentre randomized trial on consecutive children with a displaced diaphyseal both-bone forearm fracture that was stable after reduction, who visited the emergency department of one of 4 participating Dutch hospitals: Erasmus Medical Center (Rotterdam), Haga Hospital (The Hague), Reinier de Graaf Hospital (Delft), and Sint Franciscus Hospital (Rotterdam). The regional medical ethics committee approved the study and it was registered at ClinicalTrials.gov with registry identifier NCT00398242. The trial was performed in compliance with the Helsinki Declaration. Informed consent for participation was obtained from all parents and from all children aged ≥ 12 years.

We included all children aged < 16 years who sustained a displaced diaphyseal both-bone forearm fracture that was stable after reduction (Figure 1). A diaphyseal

fracture was defined as a fracture in the shaft of the bone between the distal and proximal metaphysis. The criteria for reduction are given in Table 1. Exclusion criteria were unstable fractures, fractures older than 1 week, severe open fractures (Gustilo II and III), and re-fractures.

Our primary outcome was limitation of pronation and supination 6 months after the initial trauma. The secondary outcomes were re-displacement of the fracture, limitation of flexion and extension of the wrist and elbow, complication rate, cast comfort, complaints in daily life, and cosmetics of the fractured arm.



Figure 1. Radiographs of a displaced diaphyseal both-bone fracture

PROCEDURES

A surgeon reduced the fracture in the operating room under general anaesthesia with fluoroscopic guidance. After optimal closed reduction, the fracture was tested for stability. A fracture was defined as unstable if full pronation and supination of

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

Type of deformity	Age in years	Deformity
Angulation	< 10	> 15 degrees
	10-16	> 10 degrees
Translation	< 16	> half of bone diameter
Rotation	< 16	> 0

the proximal forearm caused re-displacement of the fracture under fluoroscopic vision. This test for stability has been used before in a group of children with forearm fractures¹⁰. Unstable fractures²⁴ were excluded and treated with intramedullary nails. The remaining fractures were defined as stable and were randomized to 6 weeks of AEC or to 3 weeks of AEC followed by 3 weeks of BEC. The surgeon applied an AEC in the operation room. First, a stockinet and layer of wool were applied to protect the skin and bony prominences. Then, a well-fitted plaster slab was applied which covered approximately two-thirds of the circumference of the arm. Finally, a bandage was wrapped around the arm. The elbow was set in 90 degrees of flexion and the forearm in neutral position. All children received a sling for at least 1 week.

The children underwent clinical and radiographic evaluation by a surgeon at 1, 3, and 6 weeks after initial trauma. A cast technician revised this plaster cast to circumferential plaster cast after 1 week and applied a new circumferential synthetic cast after 3 weeks (AEC or BEC). The BEC extended only to the elbow. Fracture displacement, as defined by the loss of reduction according to the primary reduction criteria (Table 1), required new fracture reduction. Finally, the cast was removed 6 weeks after initial treatment.

An orthopaedic surgeon (JWC, who was not involved in treatment) examined all children at 2 and 6 months after the initial trauma using a standardized technique to measure flexion and extension of the wrist and elbow, in combination with pronation and supination of both arms¹¹. The pronation and supination were scaled using a previously employed grading system¹² with excellent, good, fair, and poor results for, respectively, 0–10, 11–20, 21–30, and 31 degrees of limitation. All

children with at least 30 degrees of functional impairment at the 2-month examination were referred to a physiotherapist. At the 2-month examination, the parents and children evaluated the comfort of the cast using a visual analogue scale (VAS) with highest score for maximal comfort, and a questionnaire to evaluate difficulties in performing 7 daily activities during the period of cast. This questionnaire had previously been used for a similar group of children¹³.

6 months after the initial trauma, the parents and JWC completed a VAS regarding cosmetics of the fractured arm, with highest score for similar cosmetics in the injured and uninjured arm. In the same consultation, complaints concerning the fractured arm were documented using a modified grading system. This grading system combines limitation of pronation and supination with complaints covering daily life or during strenuous activities. It had been used previously for a similar group of children¹⁴. Thereafter, the parents filled in an ABILHAND-Kids questionnaire, which is a measure of manual ability in children with upper limb impairments.

Radiographs were taken in the emergency room. These were followed by radiographs after reduction and during follow-up at 1, 3, and 6 weeks. The final radiographs were taken 6 months after the initial trauma. Angulation, translation, rotation, and shortening of fractures were measured on the radiographs to determine primary displacement, displacement during treatment with cast, and final displacement at 6 months. Rotation of the fractured bones was analysed from differences in the diameter of the diaphysis of the ulna and radius¹⁵. To assess the interrater reproducibility, the angulation of the fracture was re-measured in 45 children by a trauma surgeon. The interrater reproducibility of the radiological assessment showed an intraclass correlation (ICC) of 0.81 (95% CI: 0.68–0.89) and 0.89 (95% CI: 0.81–0.94) for the radioulnar angulation of the ulna and radius, respectively. The ICC of sagittal angulation was 0.92 (95% CI: 0.85–0.95) for the ulna and 0.87 (95% CI: 0.77–0.92) for the radius.

Randomization and masking

A physician who was not involved in treatment randomized the children using sealed envelopes with varied block sizes. The randomization took place after the fracture was reduced and defined as stable. The study was not blinded regarding the children, parents, and clinicians. JWC collected all the data.

Statistics

This study was an equivalency study in which we wanted to determine whether the index treatment (a combination of AEC and BEC) was no better or worse than the control treatment (AEC alone). The main aim of the study was to address the question: do 6 weeks of AEC, or 3 weeks of AEC and 3 weeks of BEC, cause equal limitation of pronation and supination 6 months after the initial trauma? We assessed the numbers of children required with assumption of similarity of pronation and supination in both groups. Similarity between the 2 groups was defined as a maximum of 15 degrees less pronation or supination in the group treated with AEC and BEC. We chose 15 degrees of limitation to stay within the safe margins of good results as graded previously¹². With an a priori calculation, it was determined that with a power of 80%, a significance level of 0.05, and a standard deviation (SD) of 15 degrees, the groups should consist of 30 children each.

First, we assessed whether the variables had a normal distribution using the Shapiro-Wilk test for normality. Based on these analyses, the results are presented as mean (SD). The primary research question was examined using linear regression analysis. If necessary, adjustments for unbalanced covariates were made. To check for linearity, we plotted the standardized residuals of the variables used against the standardized predicted values. If there was doubt with respect to violation of assumptions regarding distribution of residuals, we carried out a Mann-Whitney test comparing the 2 groups regarding the average of the measurements. Differences between both groups (AEC vs. AEC plus BEC) for the secondary outcome measures were analysed by one-way ANOVA to correct for multiple comparisons (Bonferroni). Statistical analysis was performed with SPSS software version 17.0.

RESULTS

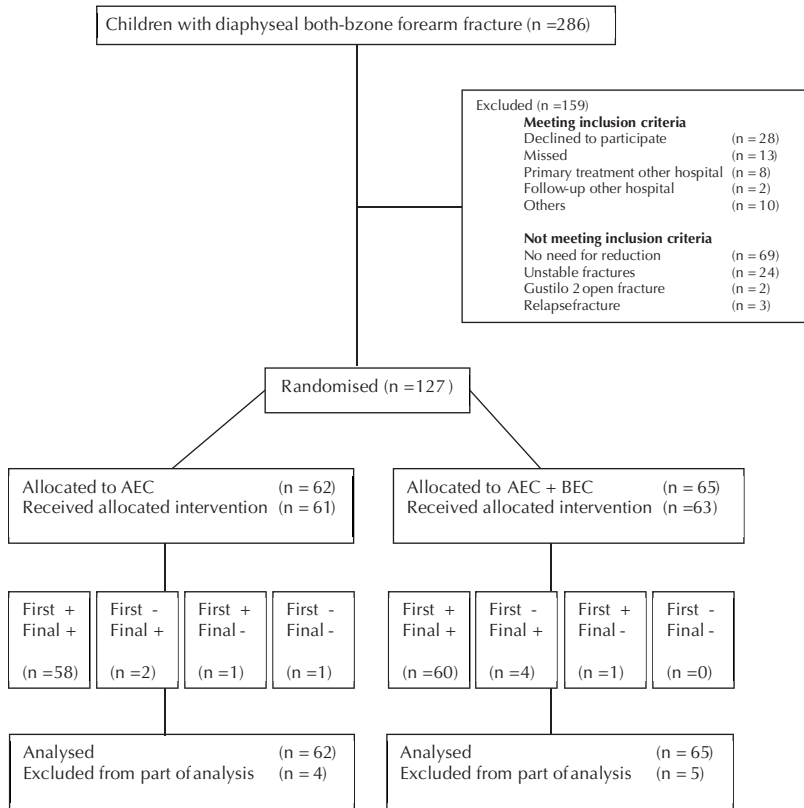
Between January 2006 and August 2010, 127 children were included in the study. 62 children were randomized to 6 weeks of AEC and 65 children were randomized to 3 weeks of AEC followed by 3 weeks of BEC (Figure 2). Despite the randomization, there was a substantial difference in age at the time of fracture, dominant arm fractured, and fracture type of the radius (Table 2). For this reason, the statistical analyses were corrected for these baseline variables.

Fractures were reduced in the operating room in 68% of the children in the AEC group and in 70% of the children in the other group (AEC and BEC). The remaining fractures were reduced at the emergency department. The follow-up rate was 98%, with a mean follow-up time of 6.9 (4.7–12.9) months.

At 6-month follow-up, the mean limitation of pronation and supination was 18 degrees (95% CI: 0–50) for children treated with AEC, and 11 degrees (CI: 0–34) for children treated with AEC and BEC ($p = 0.05$). With and without adjustment for unbalanced covariates, no significant differences in primary outcome were found (Table 3).

Using the grading system for limitation of pronation and supination¹², the results in the AEC-alone group were excellent in 21%, good in 38%, fair in 26%, and poor in 15%. In the group treated with AEC and BEC, the results were excellent in 33%, good in 37%, fair in 27%, and poor in 3%. Similar results were found using the modified grading system¹⁴. In the AEC group, the results were excellent in 33%, good in 42%, and fair in 25%. In the group treated with AEC and BEC, the results were excellent in 48%, good in 30%, fair in 20%, and poor in 2%.

The secondary outcome measures showed a higher VAS for comfort in the group of children treated with AEC and BEC ($p < 0.001$) (Table 4).



n = number of children; AEC = above elbow cast; BEC = below elbow cast; First: first examination; Final: final examination; + : examined; - : not examined.

Figure 2. *Flowchart of enrolment in the study*

Chapter 5

Table 2. *Baseline characteristics of the study population*

	Total	AEC	AEC + BEC
Number of children	127	62	65
Age at time of fracture, years mean (SD)	7.9 (3.2)	8.7 (3.3)	7.1 (2.9)
Male sex	69	69	68
Dominant arm fractured	38	24	52
Fracture type radius*			
Greenstick	46	34	58
Complete	54	66	42
Location of fracture of radius, (mean \pm SD)	49	50 (13)	49 (14)
Fracture type ulna			
Greenstick	55	48	63
Complete	45	53	38
Location of fracture of ulna, (mean \pm SD)	37	39 (13)	35 (10)

AEC: Above Elbow Cast; BEC: Below Elbow Cast; Values are presented as percentage unless stated otherwise;

The location of the fracture was calculated by dividing the distance of the fracture to the wrist by the length of the bone.

Table 3. *Data on limitation of pronation and supination of the fractured arm*

	AEC	AEC + BEC
2 months after fracture		
None	7	13
1-10	20	31
11-20	25	20
21-30	15	8
>31 degrees	32	28
Mean limitation / 95% CI	28 [0; 72]	21 [0; 57]
6 months after fracture		
None	21	33
1-10	20	28
11-20	30	22
21-30	12	11
>31 degrees	18	6
Mean limitation / 95% CI	18 [0; 50]	11 [0; 34]

AEC: Above-elbow cast; BEC: Below-elbow cast; Data are presented as percentage; With and without adjustment for unbalanced covariates no significant differences were found.

Chapter 5

Table 4. *Data on secondary outcomes*

	AEC	AEC + BEC
VAS cast comfort*	4.4 (2.3)	8.1 (1.8)
VAS cosmetics fractured arm by parents	7.8 (2.2)	8.6 (1.9)
VAS cosmetics fractured arm by orthopaedic surgeon	8.0 (2.0)	8.9 (1.6)
Total ABILHAND score at final clinical examination	40 (7.5)	41 (5.3)
Total complications, %	52	39
Secondary dislocation, %	37	31
Secondary reduction, %	11	3
Days in cast	44 (8)	44 (5)
Days until first clinical examination	79 (26)	78 (26)
Days until final clinical examination	211 (43)	208 (38)
Referral to physiotherapy, %	59	38
Number of visits to physiotherapy	4.1 (5.8)	2.2 (4.0)
Limitation of wrist flexion-extension of the fractured arm (degrees)	3.4 (6.9)	1.6 (3.8)
Limitation of elbow flexion-extension of the fractured arm (degrees)	1.2 (4.4)	0.5 (1.9)

Values are presented as mean (SD) unless stated otherwise; VAS: Visual Analogue Scale; * Significant difference ($p < 0.001$) after correcting for imbalance of baseline variables, namely age, dominant arm and type of fracture radius.

Table 5. *Data on complications*

	AEC	AEC + BEC
Displacement during cast	23	20
Re-fracture	5	3
Transient neuropraxia	2	2
Excoriation elbow crease	1	-
Nonunion	1	-
Total complications	32	25

AEC = above-elbow cast; BEC = below-elbow cast; Values are presented as number of complications; No significant difference was found between the two groups.

The questionnaire¹³, which evaluated difficulties during the period of cast, gave similar results between the 2 groups.

There were 32 complications in 27 children treated with AEC and 25 complications in 23 children treated with AEC and BEC (Table 5). Most complications consisted of fracture re-displacement. Almost half of all re-displacements occurred in the group with reduction of the fracture in the emergency department, and all re-displacements occurred during the first 3 weeks. 9 of 43 re-displaced fractures were reduced again and treated after reduction with cast in 4 children, and with intramedullary nails and cast in 5 children. In 34 children, the re-displacement of the fracture was accepted. Furthermore, greenstick and complete fractures showed a similar rate of re-displacement.

At final follow-up, 23 children (12 of whom were aged ≥ 10 years) developed a malunion as defined by our primary reduction criteria (Table 6). Although all 23 fractures showed re-displacement in cast, 3 were reduced a second time. The malunion was localized in the proximal half of the diaphysis of the radius and of the ulna in 15 and 3 children, respectively. Of the 23 children with a malunion, 7 regained almost full pronation and supination while 8 children suffered from a limitation of ≥ 31 degrees.

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Table 6. *Radiological outcomes*

	AEC				AEC + K-wires			
	Trauma	After reduction	Removal of cast	Final	Trauma	After reduction	Removal of cast	Final
Angulation								
PA ulna	13 (\pm 9)	3 (\pm 3)	4 (\pm 3)	6 (\pm 4)	13 (\pm 12)	4 (\pm 4)	6 (\pm 4)	6 (\pm 4)
PA radius	14 (\pm 8)	5 (\pm 3)	6 (\pm 4)	6 (\pm 4)	12 (\pm 10)	6 (\pm 3)	7 (\pm 5)	7 (\pm 5)
Lateral ulna	25 (\pm 18)	6 (\pm 5)	5 (\pm 5)	4 (\pm 4)	26 (\pm 16)	6 (\pm 4)	7 (\pm 5)	6 (\pm 4)
Lateral radius	28 (\pm 17)	9 (\pm 5)	10 (\pm 6)	8 (\pm 5)	28 (\pm 16)	7 (\pm 5)	9 (\pm 5)	8 (\pm 5)
Translation								
PA ulna	7 (\pm 20)	3 (\pm 8)	*	*	3 (\pm 9)	3 (\pm 9)	*	*
PA radius	3 (\pm 8)	5 (\pm 11)	*	*	11 (\pm 21)	11 (\pm 19)	*	*
Lateral ulna	10 (\pm 27)	7 (\pm 17)	*	*	9 (\pm 23)	11 (\pm 24)	*	*
Lateral radius	9 (\pm 25)	4 (\pm 10)	*	*	9 (\pm 26)	13 (\pm 23)	*	*
Shortening of radius and/or ulna								
%	13.8				13.6			
Rotation of radius and/or ulna								
%	6.2				1.7			

Angulation: Radioulnar angulation (PA ulna, PA radius) and sagittal angulation (Lateral ulna, Lateral radius) presented in degrees as mean (\pm standard deviation).

Translation: Radioulnar translation (PA ulna, PA radius) and sagittal translation (Lateral ulna, Lateral radius) presented in percentage of the width of ulna or radius as mean (\pm standard deviation).

Shortening and rotation as percentage of appearance.

*Translation not relevant because of formation of callus.

No significant differences between AEC and AEC + BEC group are found.

DISCUSSION

We found that in the treatment of reduced stable diaphyseal both-bone forearm fractures in children, conversion from AEC to BEC was safe 3 weeks after the initial trauma. Limitation in flexion and extension of the elbow did not occur in either of the groups.

We found a limitation of pronation and supination of 30 degrees at final follow-up in 15 of 127 children, 8 of whom also suffered a radiographic malunion. 6 children with a radio-graphic malunion at final follow-up showed no limitation of pronation and supination. These findings demonstrate that limitation of pronation and supination is caused by malunion and contractures, as previously stated by other authors^{1,2,4,5,16,17}. The idea of contractures of injured soft tissue being a cause of limitation of pronation and supination was supported by a trend of better forearm rotation in the BEC group, in which children could rotate the forearm early to prevent contractures.

Compared with previous studies, limitation of pronation and supination was relatively high in our children. Using the grading system¹², we found that 21% (AEC) and 33% (AEC and BEC) had excellent results, whereas other authors have found excellent results in 44–100% of such children^{9,12,14,18-20}. The modified grading system¹⁴ resulted in 33% and 48% excellent results in our 2 groups, as compared to 82% in another study¹⁴. Our prospective analysis, inclusion of only the more severe both-bone forearm fractures, and the high percentage of malunions may have been responsible for our less favourable results.

Previous studies have found a re-displacement rate of 7–27% in non-operatively treated forearm fractures, whereas we found a rate of 4%^{9,18,20-24}. Our higher rate of re-displacement might be explained by our strict malunion criteria, the prospective follow-up with scheduled radiographs, our test for stability, and the type of cast (non-circumferential cast applied directly after reduction). Although BEC allows free movement of the elbow, in our study conversion to BEC after 3 weeks did not cause re-displacement of fractures. In our patients, all re-displacements occurred in the AEC group during the first 3 weeks of treatment.

In the statistical analysis, we were aware that strict correction for multiple testing was not necessary because of the evaluation of predefined hypotheses.

However, we chose a conservative method to test the secondary outcome parameters. In addition, we also tested the secondary outcome without correction for multiple testing (using a p-value of 0.05), and even then no differences were found between groups.

Our study had several limitations. First, several fractures were reduced at the emergency department instead of in the operating room. The slightly higher rate of re-displacement in fractures reduced at the emergency department (42% vs. 30%) led us to suspect that testing of fracture stability without anaesthesia and fluoroscopy is less optimal. Fortunately, there was an equal distribution of fractures reduced in the emergency room in the 2 groups, and this study investigated treatment modalities after reduction. Secondly, not all re-displaced fractures were reduced following our study protocol. This was probably due to the expectation of correction of the malunion by growth, and the reluctance of the surgeon to propose a second reduction in view of the effect on the child. Thirdly, the outcome of the test for stability after reduction was a subjective opinion of the treating physician. No tests for stability of fractures are objective, and the test used was the only one to appear in literature (25). The final limitation was our (short) period of follow-up in this young population with a capacity for correction by growth. Nevertheless, these diaphyseal fractures (especially in older children) show less correction than distal metaphyseal fractures in younger children.

In summary, our results suggest that reduced stable diaphyseal both-bone forearm fractures in children can be safely treated by 3 weeks of above-elbow cast and 3 weeks of below-elbow cast. Re-displacement of the fracture might be identified early by radiography at set times.

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CHAPTER 6

Single-bone intramedullary fixation of unstable both-bone diaphyseal forearm fractures in children leads to increased re-displacement: a multicentre randomised controlled trial

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ABSTRACT

Introduction: Both-bone diaphyseal forearm fractures in children can be stabilised without cast by a flexible intramedullary nail in both the radius and the ulna. Adequate results with single-bone fixation combined with a complementary cast are also reported. However, because those results are based on a selection of children, this trial investigates whether single-bone intramedullary fixation, compared with both-bone intramedullary fixation, results in similar pronation and supination in children with an unstable diaphyseal both-bone forearm fracture.

Materials and methods: In four Dutch hospitals, 24 consecutive children aged < 16 years with a displaced unstable both-bone diaphyseal forearm fracture were randomly allocated to single-bone or both-bone intramedullary fixation. Primary outcome was limitation of pronation and supination 9 months after initial trauma. Secondary outcomes were limitation of flexion/extension of wrist/elbow, complication rate, operation time, cosmetics of the fractured arm, complaints in daily life, and assessment of radiographs.

Results: Between January 2006 and August 2010, 11 children were randomised to single-bone fixation and 13 to both-bone fixation. In the both-bone fixation group, two fractures were stabilized by only one nail. In both groups, median limitation of pronation/supination at 9-months follow-up was 5-10 degrees. In both groups operation time was similar but in the single-bone fixation group cast immobilisation was longer (median of 37 vs. 28 days). In four children, re-displacement of the fracture occurred in those fractures without an intramedullary nail.

Conclusions: These results caution against the use of single-bone fixation in all both-bone forearm fractures. This method may lead to increased re-displacement and reduced clinical results.

INTRODUCTION

Diaphyseal both-bone forearm fractures are frequently seen in children. During impact of trauma, the high energy level often results in a displaced fracture. The displacement generally needs to be corrected and stabilised by a cast, intramedullary nails and/or plates.

Fixation by intramedullary nails has gained popularity because of good clinical and radiographic results¹⁻⁶. Flexible intramedullary nails are generally used to stabilise paediatric fractures with two nails⁷⁻⁹. Initially, one pre-bent nail is inserted in the relatively straight intramedullary canal and creates a bending moment. Then, a second pre-bent nail is inserted with the concavity of the nail opposite the first one creating a counteracting force which stabilises the fracture. Furthermore, both-bone forearm fractures fixated with two intramedullary nails do not need stabilisation by a complementary cast.

In contrast to single-bone fractures, with both-bone forearm fractures the narrow intramedullary canal of the radius and ulna makes insertion of two nails in one bone impossible. For that reason the radius and ulna are fixated separately with a single flexible intramedullary nail, with the concavity of the nails in the same direction. This results in an absence of the stabilising effect of the counteracting force of two nails with opposite concavity.

As an alternative, the possibility of single-bone fixation in both-bone forearm fractures combined with a complementary cast has been studied^{2,5,10-17}. Single-bone intramedullary fixation in both-bone forearm fractures offers both advantages and disadvantages. Although insertion and removal of only one nail can reduce operation time and complications, the bone without fixation has a tendency to displace necessitating immobilisation in a cast.

To date, only one study (20 children, no controls) has prospectively investigated single-bone fixation in both-bone forearm fractures¹², whereas others used a retrospective design^{2,5,10-13,16-19}. Most studies concluded that single-bone intramedullary fixation of both-bone diaphyseal forearm fractures in children is a safe and efficacious option with good functional and radiological results^{2,5,10-13,16-19}. Nevertheless, these results were based on a selection of children who sustained a both-bone forearm fracture that remained aligned and stable after single-bone fixation^{2,5,10-13,16-19}.

To systematically compare the value of the two types of fixation, the present randomised study investigates whether single-bone intramedullary fixation, compared with both-bone intramedullary fixation, results in similar pronation and supination in children with an unstable diaphyseal both-bone forearm fracture.

PATIENTS AND METHODS

Trial design and participants

A multicentre randomised controlled clinical trial was performed including all consecutive children with a displaced unstable diaphyseal forearm fracture of the radius and ulna. These children visited the emergency department of one of the four participating Dutch hospitals: Erasmus Medical Center (Rotterdam), HAGA Hospital (The Hague), Reinier de Graaf Hospital (Delft) and Sint Franciscus Hospital (Rotterdam).

The regional Medical Ethics committee approved the study (registered in ClinicalTrials.gov: NCT00314587). Informed consent was obtained for participation from all parents and from all children aged ≥ 12 years.

Included were all children aged < 16 years who sustained a displaced diaphyseal both-bone forearm fracture that was unstable after reduction (Fig. 1).



Figure 1. *Single-bone intramedullary fixation of both-bone diaphyseal forearm fracture.*

A diaphyseal fracture was defined as a fracture in the shaft of the bone between the distal and proximal metaphysis. The criteria for reduction were *a priori* defined and based on previous studies²⁰⁻²⁹, i.e. in children aged < 10 years an angulation of > 15 degrees, translation of $>$ half the diameter of the bone, or any rotation, was defined as displaced. For children aged 10-16 years, an angulation of > 10 degrees, translation of $>$ half the diameter of the bone, or any rotation, was defined as displaced.

Exclusion criteria were stable fractures, fractures older than 1 week, severe open fractures (Gustilo II and III)³⁰, and re-fractures.

Primary outcome was limitation of pronation and supination compared to the uninjured arm, 9 months after the initial trauma. Secondary outcomes were limitation of flexion/extension of wrist and elbow, complication rate, operation time, cosmetic results, complaints in daily life, and assessment of radiographs.

Procedure

A surgeon reduced the fracture under fluoroscopic guidance (in the operating room) with the child under general anaesthesia. After optimal reduction, the fracture was tested for stability. A fracture was defined as unstable if maximal pronation/supination of the proximal forearm caused re-displacement of the fracture. This test for stability has previously been used in children with a forearm fracture (19). Stable fractures were excluded and treated with cast immobilisation.

The unstable fractures were randomised between single-bone and both-bone intramedullary fixation. In case of allocation to single-bone fixation, the surgeon could stabilise the most unstable bone with an intramedullary nail. Titanium Elastic Nails (Synthes®) were used, with a diameter of 2.0-3.0 mm depending on individual patient anatomy. After incision of the skin and blunt dissection, the radius was pinned retrograde via an entry hole proximal to the distal physis, while the ulna was pinned anterograde via an entry hole distal to the olecranon physis. If reduction or insertion of the intramedullary nail failed by closed means, the fracture was opened by small incision. The nails were either buried or left transcutaneous, depending on the surgeon's choice. After stabilisation of either the ulna or radius or both bones, the surgeon applied an above-elbow cast in the operation room. Primarily a stockinet and layer of wool were applied to protect the skin and bony prominences. Secondly a well-fitted plaster slab was applied which covered approximately 2/3 of the circumference of the arm. Finally, a bandage was wrapped around the arm. The elbow was set in 90 degrees of flexion and the wrist in neutral position. All children received a sling for at least 1 week.

All children underwent clinical and radiological evaluation at 1, 3 and 6 weeks after the initial trauma by a surgeon. A cast technician revised and renewed the cast where necessary. Re-displacement, as defined by the loss of reduction according to

the primary reduction criteria, required secondary reduction and intramedullary fixation of both bones. The cast was removed 3 weeks after initial treatment. The nails were removed in the outdoor patient clinic if left transcutaneous during the first 2 months, or in the operation room if buried during the first 8 months.

One orthopaedic surgeon, who was not involved in the primary treatment, examined all children 2 and 9 months after initial trauma using a standardised technique to measure flexion/extension of wrist and elbow in combination with pronation/supination of both arms³¹. The pronation/supination was scaled using the grading system as described by Daruwalla with excellent, good, fair and poor results for 0, 11-20, 21-30 and more than 31 degrees of limitation, respectively²². Patients with at least 30 degree of functional impairment at the 2-months examination were referred to a physiotherapist.

Nine months after the initial trauma final posteroanterior and lateral radiographs were taken. In the same consultation, both the parents and the orthopaedic surgeon completed a VAS cosmetics of the fractured arm with maximum score for similar appearance of the fractured and non-fractured arm. Thereby, complaints of the fractured arm were documented by a modified grading system. This grading system combines the limitation of pronation/supination with complaints in daily life or during strenuous activities; this system was successfully applied in a similar group of children³². Furthermore, the parents filled in an ABILHAND-Kids questionnaire³³: this is a measure of manual ability for children with upper limb impairments. The scale is validated for children with cerebral palsy and measures a child's ability to manage daily activities that require the use of the upper limbs, with a maximum score of 42 for no impairments.

The orthopaedic surgeon measured all available radiographs to determine primary displacement, displacement during treatment with cast immobilisation, and final displacement at 9-months follow-up.

Randomisation and masking

A physician (who was not involved in the treatment) randomised the children by sealed envelopes with varied block sizes. The orthopaedic surgeon examined all children 2 and 9 months after initial trauma and measured the radiographs without masking. Obviously, the children and parents were not blinded for treatment.

Statistical methods

The primary aim of the study was to investigate whether single-bone fixation, compared with both-bone fixation, causes equal limitation of pronation/supination at 9-months post-trauma. To assess the number of children required, an equivalence test was used to demonstrate the similarity of pronation/supination in both groups. Equivalence between the two groups was defined as a maximum of 15 degrees less pronation or supination in the group treated with single-bone fixation after 9 months. For this study, we decided on 15 degrees of limitation in order to remain in the safe margin of good results as graded previously²². With an *a priori* calculation it was determined that with a power of 80%, an alpha of 0.05 and a standard deviation of 15 degrees, each group should consist of 30 children.

First, 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 median and interquartile range (IQR). The primary research question was analysed using linear regression analysis (limitation of pronation/supination of the fractured arm 9 months after initial trauma as dependent variable, and intervention as independent variable). If necessary, adjustments for unbalanced covariates were made. Differences between the groups for the secondary outcome measures were analysed by one-way ANOVA to correct for multiple comparisons (Bonferroni).

Patients were analysed according to the intention to treat principle for the primary and secondary outcomes. Additionally, we performed a per protocol analysis, in which the patients were analysed according to the intervention they finally received.

Statistical analyses were performed with SPSS 17.0 (SPSS Inc., Chicago, USA).

RESULTS

Between January 2006 and August 2010 a total of 24 children were included: of these, 11 were randomised to single-bone fixation and 13 to both-bone fixation (Fig. 2). The group with single-bone fixation consisted of 7 fractures with fixation of only the radius, and 4 with fixation of only the ulna. The group randomised to both-bone fixation consisted of 11 fractures with fixation of both the ulna and radius, and 2 with fixation of only the ulna. For the latter 2 children, the change in treatment was on one occasion caused by a life-threatening problem elsewhere in the hospital, and on another occasion by an exhausting procedure of 180 min with an apparent stable fixation of both-bones by fixation of only the ulna. Because the two children with a change in treatment had poor results, we decided to present both the intention-to-treat analysis and per-protocol analysis.

Table 1 presents the baseline characteristics of the total study population and per randomisation. In the group allocated to single-bone fixation one child had a grade 1 open fracture. Two fractures in this latter group needed an open reduction, whereas in the group with both-bone fixation 6 fractures needed an open reduction. Of the 2 children treated with single-bone fixation instead of the allocated both-bone fixation, both needed an open reduction. All children in the study attended the final examination.

Table 1. *Baseline characteristics of the study population.*

	Total	1-bone fixation		2-bone fixation	
		ITT	PP	ITT	PP
No. of children	24	11	13	13	11
Median age at time of fracture in years (IQR)	10.4 (6.8)	8.8 (6.0)	9.1 (6.3)	11.5 (5.5)	10.9 (7.2)
Gender, % male	58.3	45.5	53.8	69.2	63.6
Dominant arm fractured (%)	41.7	36.4	38.5	46.2	45.5
Type fracture radius (%)					
Greenstick	30.4	36.4	33.3	25.0	27.3
Complete	69.6	63.6	66.7	75.0	72.7
Type fracture ulna (%)					
Greenstick	30.4	36.4	33.3	25.0	27.3
Complete	69.6	63.6	66.7	75.0	72.7
AO classification (n)*					
22-D/2.1	3	2	2	1	1
22-D/4.1	11	4	6	7	5
22-D/5.1	9	5	5	4	4
22-D/5.2	1	0	0	1	1

IQR = interquartile range; ITT = intention to treat analysis; PP = per protocol analysis; *AO classification of paediatric long-bone fractures.

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Table 2. *Data on limitation of pronation and supination of the fractured arm.*

	1-bone fixation		2-bone fixation	
	ITT	PP	ITT	PP
Two months after fracture				
No. of children	11	13	13	11
None	0	0	0	0
1-10 degrees	3	3	2	2
11-20 degrees	3	3	4	4
21-30 degrees	3	3	3	3
>31 degrees	2	4	4	2
Median limitation in degrees (IQR)	20 (15)	25 (23)	25 (25)	20 (15)
Nine months after fracture				
	ITT	PP	ITT	PP
No. of children	11	13	13	11
None	3	3	5	5
1-10 degrees	5	5	2	2
11-20 degrees	3	3	4	4
21-30 degrees	0	0	0	0
>31 degrees	0	2	2	0
Median limitation in degrees (IQR)	10 (15)	10 (18)	10 (20)	5 (15)

Data are presented as number of children; ITT = intention to treat analysis; PP = per protocol analysis;

IQR: interquartile range.

Table 2 shows the median limitation of pronation/supination at 2 and 9 months follow-up. For both groups, the median limitation of pronation/supination at 9 months was 5-10 degrees. A malunion, as defined by primary reduction criteria, was found in 3 children at final follow-up with 5, 20 and 40 degrees limitation of pronation/supination, respectively. One of these 3 children suffered from an open fracture and another one needed an open reduction and sustained a re-fracture. These 3 children were aged 10, 11 and 13 years, respectively.

Table 3. Grading system of limitation of pronation and supination.

	Grading by Daruwalla (19)				Modified grading by Price et al. (29)			
	1-bone fixation		2-bone fixation		1-bone fixation		2-bone fixation	
	ITT	PP	ITT	PP	ITT	PP	ITT	PP
N	11	13	13	11	11	13	13	11
Excellent	3	3	5	5	5	5	5	5
Good	6	6	4	4	4	4	2	2
Fair	2	2	2	2	2	3	5	4
Poor	-	2	2	-	-	1	1	-

ITT = intention to treat analysis; PP = per protocol analysis; N = number of children.

Table 4. Data on secondary outcomes.

	1-bone fixation		2-bone fixation	
	ITT	PP	ITT	PP
No. of children	11	13	13	11
VAS cosmetics fractured arm by parents	8.3 (2.4)	8.3 (2.9)	8.5 (2.8)	9.0 (1.6)
VAS cosmetics fractured arm by orthopaedic surgeon	8.8 (1.5)	8.4 (3.8)	7.7 (3.9)	8.0 (3.6)
Total ABILHAND score at final clinical examination	42.0 (1.0)	42.0 (1.0)	42.0 (0.5)	42.0 (0)
≥ 1 complication, %	36.4	46.2	30.8	18.2
No. of days in cast	37.0 (21.0)	37.0 (20.5)	28.0 (16.5)	22.0 (16.0)
Operation time in minutes	67 (82)	67 (81)	60 (68)	60 (63)
Days until removal of hardware	57.5 (204.5)	80.5 (208.5)	184.5 (173.0)	184.5 (176.5)
Days until first clinical examination	74.0 (66.0)	70 (60)	54.0 (71.5)	52 (78)
Days until final clinical examination	338.0 (70.0)	309 (78.5)	292.0 (54.0)	293 (51.0)
Referral to physiotherapy, %	45.5	53.8	69.2	63.6
Limitation of wrist flexion-extension of the fractured arm (degrees)	0 (5.0)	0 (7.5)	0 (15.0)	0 (15.0)
Limitation of elbow flexion-extension of the fractured arm (degrees)	0 (0)	0 (2.5)	0 (0)	0 (0)

Values are presented as median (interquartile range) unless stated otherwise; VAS: visual analogue scale; ITT = intention to treat analysis; PP = per protocol analysis.

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Table 3 gives the results of the (modified) grading systems of the limitation of pronation and supination.

For the secondary outcome measures (Table 4), children with single-bone fixation were treated for a longer period with cast and had earlier removal of the hardware; however, the operation time was similar for both groups.

Table 5 presents the complications in both groups. Re-displacement of the fracture occurred in four children (11, 12, 16 and 19 degrees of angulation, respectively) during the first 6 weeks and only of fractures without an intramedullary nail. One child sustained a re-fracture after removal of the nails, while another child had a re-fracture of both the radius and ulna with bending of the nails inside the bones. Only the re-fractures were secondarily reduced. Furthermore, one superficial infection was seen and treated with oral antibiotics. One child who was treated with single-bone fixation of the ulna developed a non-union of the ulna and was successfully treated with removal of the nail, open reduction and internal fixation with a plate.

Table 5. *Complications occurring in the present study.*

	1-bone fixation		2-bone fixation	
	ITT	PP	ITT	PP
No. of children	11	13	13	11
Re-displacement of fracture	3	4	1	0
Transient neurapraxia	1	2	2	1
Re-fracture	1	1	1	1
Excoriation skin	1	1	0	0
Superficial infection	0	0	1	1
Nail removal impossible	0	0	1	1
Nonunion	0	1	1	0
No. of complications	6	9	7	4

Data are presented as number of children; ITT = intention to treat analysis; PP = per protocol analysis.

DISCUSSION

This study compared single-bone and both-bone intramedullary fixation of unstable diaphyseal both-bone fractures in children and indicates that single-bone fixation leads to increased re-displacement and poorer clinical outcome. Although the median limitation of pronation/supination was similar in both groups, a higher rate of complications occurred in the single-bone fixation group. These complications were mainly caused by re-displacement of the fracture without a nail. Furthermore, fractures stabilised with only one nail were immobilised in a cast for a longer period. Surprisingly, the operation time was similar in both groups. These findings in combination with the risks of infection and anaesthesia (for insertion and removal of the nails), makes us believe that a child has virtually no profit from the treatment of single-bone fixation compared with reduction and conservative treatment in cast. In our opinion, unstable both-bone forearm fractures should be treated with two intramedullary nails with cast.

At 9-months follow-up, in both groups a relatively large number of children had a limitation of pronation/supination of ≥ 20 degrees. This group of children was diverse: 2 had a malunion at final examination, 1 child was operated on a second time because of a non-union, another child re-fractured his forearm, and 2 children were treated without complications but were immobilised in cast for 37 and 42 days, respectively. Therefore, in our study population the cause of the limitation of pronation/supination seems to be multifactorial.

Other studies investigating intramedullary stabilisation of both-bone forearm fractures reported that limitation of pronation/supination occurs in 0-20% of patients^{2,5,11,12,14,16-19,34-41}, whereas this occurred in 67% of our group. A possible explanation for our high rate is our prospective study design with no children lost to follow-up, and our high rate of complications resulting in less favourable outcomes.

In other studies, the overall better results of single-bone fixation can be explained by their selective treatment of fractures with single-bone or both-bone fixation^{2,5,10-14,16-19}. In those studies, the surgeon could choose per-operatively for single-bone or both-bone fixation depending on the stability of the fracture, whereas we used a randomisation protocol irrespective of the level of stability.

In the present study, re-displacement of the fracture occurred in 4 children and only in those treated with single-bone fixation. Not surprisingly, all re-displacements

were seen in the bone without intramedullary fixation. Such re-displacement in single-bone intramedullary fixation of both-bone forearm fractures is not uncommon^{2,5,10,13}. Therefore, in children, we suggest that unstable both-bone diaphyseal forearm fractures should be stabilised with an intramedullary nail in both the radius and ulna to prevent re-displacement.

Study limitations

Some study limitations need to be addressed. First, the number of included children is small: of the 249 children with a displaced diaphyseal both-bone forearm fracture only 24 were classified as unstable. This rareness of unstable fractures is reflected in other studies with small numbers of children^{10-14,17,18,42,43}. Nevertheless, the possibility exists that our test for fracture stability was inadequate or not properly accomplished. Although we present the first randomised controlled trial of single-versus both-bone intramedullary fixation, our study was statistically underpowered and the results should be interpreted with caution.

Second, the follow-up period was only 9 months. Although this seems short, in other children treated for displaced forearm fractures no change was found in clinical or radiographic status from 6 months post-treatment until final follow-up at (mean) 2.8 years⁴⁴. Another group described a persistent limitation during long-term follow-up despite correction by growth⁴⁵, and others advised an osteotomy to correct malunion as early as 6 months after trauma⁴⁶. Although malunions in children can correct with growth, these diaphyseal malunions are less likely to correct than distal malunions because of the relatively long distance to the most active distal growth plate.

Conclusion

The results of this first randomised controlled study caution against the use of single-bone fixation in all displaced unstable both-bone diaphyseal forearm fractures in children. The single-bone fixation method may lead to increased fracture re-displacement and poorer clinical results.

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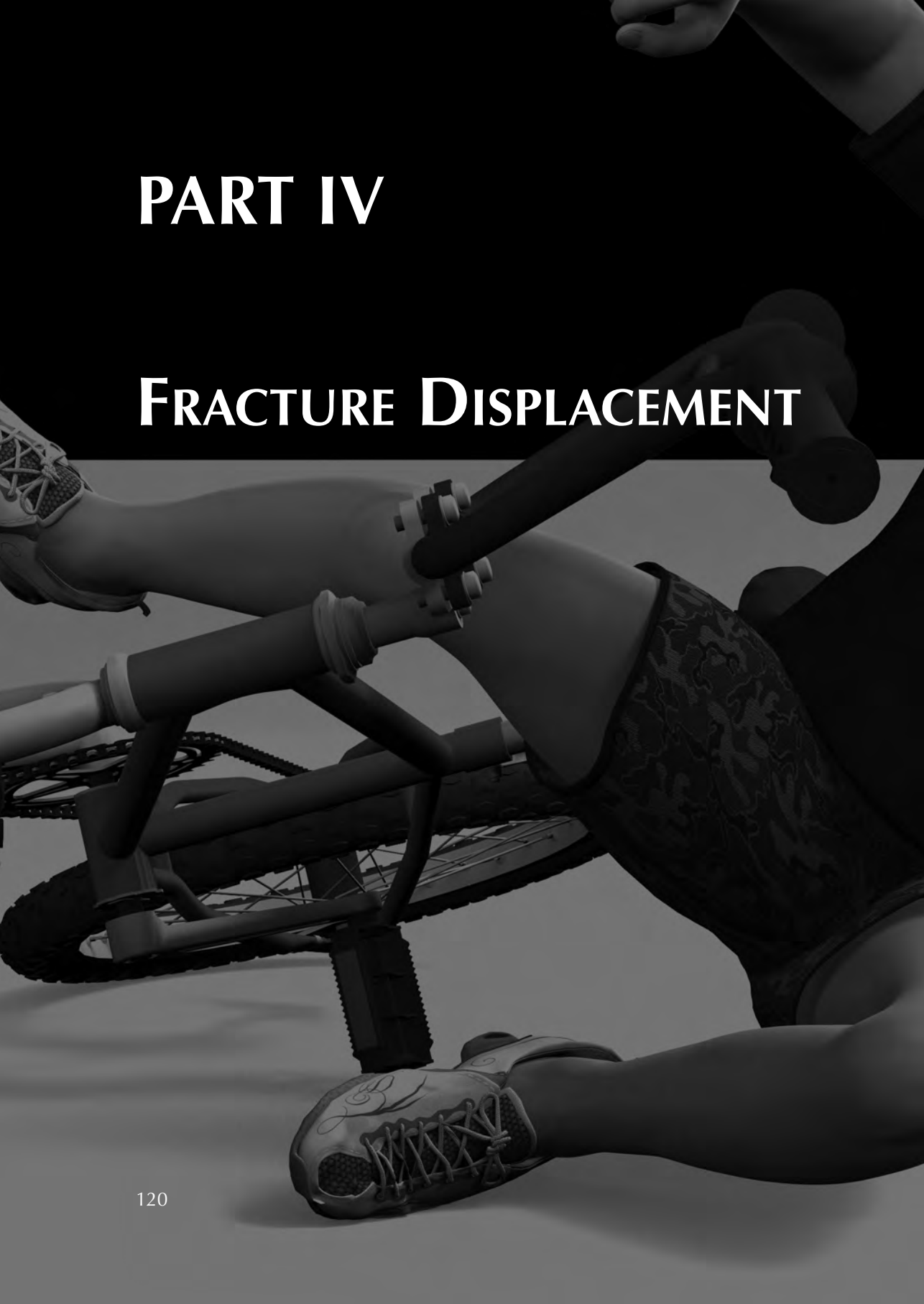
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PART IV

FRACTURE DISPLACEMENT



CHAPTER 7

Risk factors for the displacement of fractures of both bones of the forearm in children

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ABSTRACT

Forearm fractures in children have a tendency to displace in a cast leading to malunion with reduced functional and cosmetic results. In order to identify risk factors for displacement, a total of 247 conservatively treated fractures of the forearm in 246 children with a mean age of 7.3 years (SD 3.2; 0.9 to 14.9) were included in a prospective multicentre study. Multivariate logistic regression analyses were performed to assess risk factors for displacement of reduced or non-reduced fractures in the cast. Displacement occurred in 73 patients (29.6%), of which 65 (89.0%) were in above-elbow casts. The mean time between the injury and displacement was 22.7 days (0 to 59). The independent factors found to significantly increase the risk of displacement were a fracture of the non-dominant arm ($p = 0.024$), a complete fracture ($p = 0.040$), a fracture with translation of the ulna on lateral radiographs ($p = 0.014$) and shortening of the fracture ($p = 0.019$). Fractures of both forearm bones in children have a strong tendency to displace even in an above-elbow cast. Severe fractures of the non-dominant arm are at highest risk for displacement. Radiographs at set times during treatment might identify early displacement, which should be treated before malunion occurs, especially in older children with less potential for remodelling.

INTRODUCTION

Displacement of fractures of both forearm bones in children treated in a cast has been described in between 7% and 91% of cases¹⁻⁵, and can lead to malunion with reduced functional and cosmetic results^{6,7}. Despite the high rate of displacement, there has not hitherto been an analysis of risk factors in large prospective studies^{3-5,8-11}. We therefore performed a prospective multicentre study to identify the risk factors for displacement of reduced and unreduced fractures of both bones of the forearm in children when treated in a cast.

Patients and Methods

Between January 2006 and August 2010 a total of 247 children aged < 16 years with fractures of both bones of the forearm were included in a prospective study involving four hospitals (Fig. 1, Table 1). The study had ethical approval and informed consent was obtained from all parents, and children aged > 12 years. The criteria for reduction were based on previous studies (Table 2)^{1,12-20}. Exclusion criteria were: torus fractures of both the radius and ulna; fractures sustained more than a week before presentation; severe open fractures (Gustilo II and III)²¹; and re-fractures. Exclusion criteria included those fixed with Kirschner (K-) wires or intramedullary nails, fractures without final radiographs, initially displaced fractures without reduction and reduced fractures with displacement on the first subsequent radiograph. The study protocol distinguished different types of fractures. Distal metaphyseal fractures not requiring reduction were treated with a below- or above-elbow cast for four weeks²², whereas distal metaphyseal fractures needing reduction were treated with or without K-wires and an above-elbow cast for four weeks²³. Diaphyseal fractures not requiring reduction and reduced stable diaphyseal fractures were treated for six weeks with an above-elbow cast or a combination of three weeks above and three weeks below. Unstable diaphyseal fractures were fixed with one or two intramedullary nails and three weeks in an above-elbow cast. The cast was applied in a standard way by a trained nurse in the emergency department or a surgeon in the operating room. Firstly, a stockinette and layer of wool were applied to protect the skin and bony prominences. Second, a well-fitted plaster slab was applied that covered approximately two-thirds of the circumference of the arm. Finally a bandage was wrapped around the arm.

Radiographs were taken at presentation, after reduction and during treatment. An orthopaedic surgeon (JWC) who was not involved in primary treatment measured angulation, translation as a percentage of the width of radius/ulna rotation (yes/no) and shortening (yes/no) of all fractures. Rotation was detected by differences in the diameter of the diaphysis of radius and ulna on posteroanterior and lateral radiographs²⁴.

A reduced or an unreduced fracture that showed progressive displacement (Fig. 2) during follow-up was defined as displaced if further reduction was needed according to the criteria for primary reduction (Table 2). In order to assess the inter-rater reproducibility of the radiological assessment, a trauma surgeon (LUB) who was not involved in treatment re-measured the angulation of the fracture in 45 children.

Risk factors for displacement of fractures

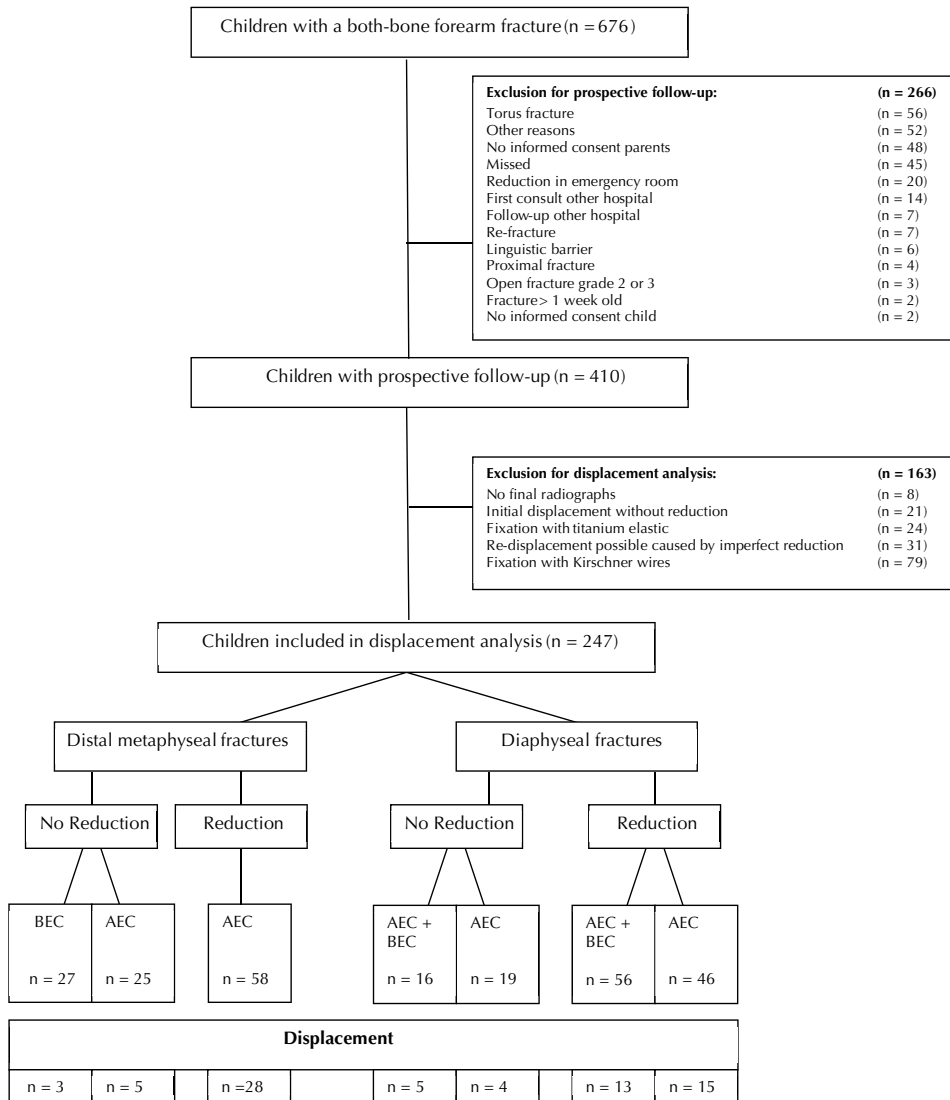


Figure 1. Flowchart of enrolment in the study (B-/AEC, below-/above-elbow cast).



Figure 2. Lateral radiographs showing a both-bone forearm fracture (left) which was properly reduced (centre) but showed re-displacement after four weeks (right). This fracture demonstrates all risk factors: complete fracture in non-dominant arm with shortening and translation of the ulna on the lateral radiograph.

Statistical analysis

Our dependent variable was displacement of the fracture in the cast and we assessed whether this was related to any of the following factors: gender, hand dominance, location of the fracture (diaphysis vs distal metaphysis), type of fracture (greenstick or complete), primary displacement (angulation, translation, shortening, rotation), reduction of the fracture, location of reduction (emergency ward, operating room), type of cast (above- or below-elbow) and quality of cast (cast-index)²⁵. Fractures other than complete were defined as greenstick fractures. The choice of risk factors was based on previous studies^{3-5,8-11,26,27}.

In order to assess which factors were related to displacement of the fracture in the cast, multivariate logistic regression analysis (enter method) was used to calculate odds ratios (ORs) including 95% confidence intervals (95% CI). In all analyses, a two-sided p-value of ≤ 0.05 was considered significant. Statistical analyses were performed with SPSS 17.0 (SPSS Inc., Chicago, Illinois).

Table 1. *Demographics*

Children	247
Mean age (yrs) (SD; range)	7.3 (3.2; 0.0 to 14.9)
Male (n, %)	147 (59.5)
Fracture on dominant arm (n, %)	98 (39.7)
Right arm fractured	96 (38.9)
Location (n, %)	
Diaphysis	137 (55.5)
Metaphysis	110 (44.5)
Type of fracture (n, %)	
Both greensticks	111 (44.9)
Both complete	64 (25.9)
Greenstick (ulna) + complete (radius)	34 (13.8)
Complete (ulna) + greenstick (radius)	17 (6.9)
Torus (ulna) + greenstick (radius)	12 (4.9)
Greenstick (ulna) + torus (radius)	4 (1.6)
Torus (ulna) + complete (radius)	4 (1.6)
Complete (ulna) + torus (radius)	1 (0.4)

Table 2. *Criteria for reduction of the fracture of radius and/or ulna based on posteroanterior and/or lateral radiographs*

Type of deformity	Age in years	Deformity
Angulation	< 10	> 15 degrees
	10-16	> 10 degrees
Translation	< 16	> half of bone diameter
Rotation	< 16	> 0

RESULTS

The fracture re-displaced in 73 children (29.6%). Re-displacement occurred more frequently in distal metaphyseal fractures compared with diaphyseal fractures (32.7% (36 of 110) vs 27.0% (37 of 137)). The mean time between the injury and displacement was 22.7 days (SD 13.5; 0 to 59), and 65 re-displacements (89.0%) were in an above-elbow cast (Fig. 2).

The factors that were significantly and independently associated with redisplacement were hand dominance and three factors associated with the severity of the fracture, namely complete fractures, translation of the ulna on lateral radiographs and shortening (Table 3, Fig. 2).

DISCUSSION

We found that 29.6% of fractures of both bones of the forearm in children treated in a cast displaced, the risk of which was increased in more severe fractures of the non-dominant arm. Earlier authors reported displacement of between 7% and 91% of fractures in the distal metaphysis^{1-5,28-31} and between 7% and 27% of fractures in the diaphysis^{4,15,26,32-35} compared with 33% and 27% respectively in our study. Our relatively high percentage of displacement can be explained by the inclusion of only both-bone fractures, which are more unstable than single-bone fractures^{5,26,36}.

Whereas an earlier study reported hand dominance as a risk factor for displacement (26), others found similar numbers in dominant and non-dominant arms (3). Our results suggest that fractures in the non-dominant arm are at increased risk for displacement, which might be explained by less stability of the fracture by less developed muscles in the non-dominant forearm.

As with earlier reports^{3-5,8,9,26} the severity of the fracture in our study seemed highly predictive of displacement. Complete fractures significantly increased the risk for displacement, a finding supported by some studies^{3-5,8,9,26} but not others^{4,11}. Whereas translation of the ulna on lateral radiographs has been reported as a risk factor for displacement³², shortening has not. Complete fractures with translation and shortening seem to be more unstable than angulated greenstick fractures with intact periosteum on one side. Angulation of the fracture did not appear to be a risk

Table 3. Factors associated with displacement of the fracture with multivariate logistic regression analysis. Only significant odds ratios are provided (CI, confidence interval); PA, posteroanterior; lat, lateral

Factors	Rate of displacement (%)	Odds ratio (95% CI)	p-value
Gender			
Male (n = 147)	29.9 (n = 44)	0.561	
Female (n = 100)	29.0 (n = 29)		
Dominant arm fractured			0.024
No (n = 149)	31.5 (n = 47)*	0.46 (0.23 to 0.89)	
Yes (n = 98)	24.5 (n = 24)*		
Fracture location			0.751
Metaphyseal (n = 110)	32.7 (n = 36)		
Diaphyseal (n = 137)	27.0 (n = 37)		
Type of fracture			0.040
Complete (n = 120)	45.0 (n = 54)	3.34 (1.63 to 6.86)	
Greenstick (n = 127)	15.0 (n = 19)		
Primary displacement §			
Angulation PA radius			0.760
Angulation lat radius			0.126
Angulation PA ulna			0.779
Angulation lat ulna			0.261
Translation PA radius			0.189
Translation lat radius			0.915
Translation PA ulna			0.952
Translation lat ulna		0.98 (0.96 to 0.99)	0.014
Shortening of radius and/or ulna			0.019
No (n = 199)	21.6 (n = 43)		
Yes (n = 48)	62.5 (n = 30)	5.67 (2.27 to 14.17)	
Rotation of radius and/or ulna			0.065
No (n = 232)	27.2 (n = 63)		
Yes (n = 15)	66.7 (n = 10)		
Reduced fracture			0.452
No (n = 87)	19.5 (n = 17)		
Yes (n = 160)	35.0 (n = 56)		
Location of reduction			0.445
Emergency ward (n = 28)	28.6 (n = 8)		
Operation room (n = 129)	36.7 (n = 47)		
Type of cast			0.085
Above-elbow (n = 188)	34.6 (n = 65)		
Below-elbow (n = 59)	13.6 (n = 8)		
Cast index §			0.597

* excluding two in whom this information was unknown

§ no dichotomous outcomes

factor for displacement in this or previous studies^{3,11,37}. Also, location in the diaphysis or metaphysis had no significant influence on displacement, a finding supported by Monga et al (26) but not Younger et al²⁷.

Although several studies considered displacement to be related to an above- or below-elbow cast^{3,10,26,27} this was not supported by our results. Also, several studies^{4,8,10,11,25,32} reported quality of the cast as a risk factor, while others found no such correlation^{9,26}. The cast index was not considered as a risk factor in our study^{25,32}.

Our study has several limitations. Because it is impossible to differentiate between imperfectly reduced and redisplaced fractures, we excluded children with reduced fractures that showed displacement at the first available radiographs after the reduction. Similarly, we could not analyse imperfect reduction as a risk factor for displacement. Furthermore, we measured the cast index in non-circumferential casts whereas this measurement is only validated for circumferential casts^{25,32}. Nevertheless, we assumed that the cast index is also important in non-circumferential casts because it indicates how well the cast is moulded to the contour of the forearm. This is supported by a study in which there were similar rates of displacement in circumferential and non-circumferential casts³.

In summary, reduced and unreduced fractures of both bones of the forearm in children displaced frequently, even if treated with an above-elbow cast. The most severe fractures in the non-dominant arm had the highest risk for displacement. Radiographs at set times during treatment might identify early displacement, which should be treated before malunion occurs, especially in older children with less potential for remodelling.

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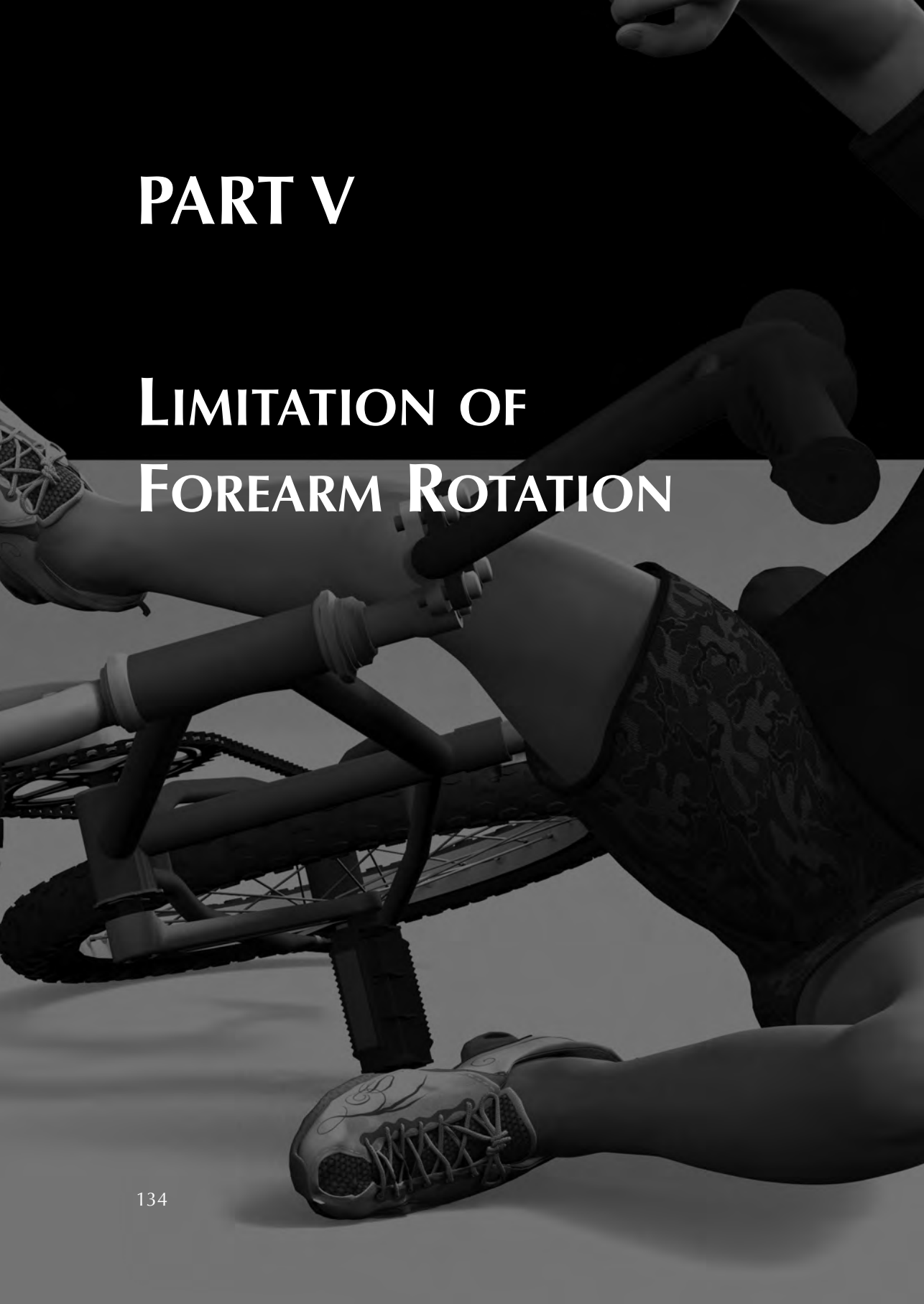
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PART V

LIMITATION OF FOREARM ROTATION



CHAPTER 8

Pronation and supination after forearm fractures in children: *reliability of visual estimation and conventional goniometry measurement.*

Injury. 2010 Jun;41(6):643-6.

Colaris J, van der Linden M, Selles R, Coene N, Allema JH, Verhaar J.

ABSTRACT

Background: Forearm fractures are common amongst children and often result in limited rotational function. In daily practice, pronation and supination of the arm are often visually estimated or measured using a conventional goniometer. The aim of this study was to compare the reliability of these two methods in paediatric patients that had previously sustained a forearm fracture.

Methods: Intra- and interrater reliability of visual estimation and conventional goniometry were determined in 47 children who had previously sustained a forearm fracture.

Results: Intra- and interrater reliability of visual estimation and conventional goniometry was fair to excellent, with Intraclass Correlation Coefficients (ICC's) ranging between 0.75 and 0.94. In addition, the overall goniometer data consistently showed lower Smallest Detectable Differences (SDD's) compared to the visual estimation data, also indicating better reliability for the goniometer method.

Conclusions: A conventional goniometer is an easy, fast and reliable method to determine the pronation and supination in a child who had sustained a forearm fracture. If an uncooperative child hinders the measurement, visual estimation is a good second choice. Measurements are more reliable when repeated by the same professional.

INTRODUCTION

Forearm rotation, consisting of pronation and supination, is commonly used in daily life for tasks such as eating, typing, picking up small objects and accepting change¹. In children up to the age of 15 years, pronation of 50-80 degrees and supination of 80-120 degrees is considered normal². In a number of pathologies, pronation and supination can be limited, such as following a forearm fracture, which is rather common among children^{1,3}. Measurement of pronation and supination limitation is important for clinical decision making and outcome evaluation for these fractures.

In the past, many devices have been developed to measure pronation and supination of the forearm. These devices include gravity-dependent methods, tubular handles, voltage gated sensors and measurements of digital photographs^{1,4-9}. For many of these devices, reliability is fair to excellent, as expressed by Intraclass Correlation Coefficients (ICCs) (10) ranging between 0.78 - 0.99 for intrarater reliability^{4,6,9} and 0.72 - 0.98 for interrater reliability^{4,5,7,9}. However, the above-mentioned devices are complex and are difficult to use in standard clinical care. In addition, they may intimidate little children. Therefore, forearm rotation in children is still generally evaluated by visual estimation or conventional goniometry. Although limitations of pronation and supination are often visually estimated in clinical practice, to our knowledge, no studies have yet investigated the reliability of visual estimation in any age group. In addition, the reliability of conventional goniometry has been investigated only scarcely in children¹, and slightly more often in adults^{4-6,9,11-13}.

Furthermore, most of the authors report the reliability of the goniometer measurements only in a healthy population^{5,6,9,11,13}, whereas only one study evaluated the reliability of measuring rotational impairments after a trauma⁴. Because visual estimation and goniometrical measurement of pronation and supination are often used in clinical care as well as in clinical research, the aim of the current study is to compare the reliability of these two methods in paediatric patients that had previously sustained a forearm fracture.

PATIENTS AND METHODS

Subjects

All patients were treated at the department of Traumatology of the Juliana Children's Hospital, The Hague, the Netherlands. The inclusion criteria for this study were: (1) patients with a midshaft or distal both-bone forearm fracture (2) the fracture was sustained in the last 2 years (3) the fracture was united (4) patients were between 6 and 16 years of age. All patients were categorised in 3 age groups: (1) 6 - 9 years old, (2) 10 - 13 years old and (3) 14 - 16 years old. The regional medical ethics committee approved the study and written informed consent was obtained for participation.

Measurements

Two different methods were used to measure the pronation-supination range of the fractured forearm: visual estimation and conventional goniometry. 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 degrees with the forearm in mid-position and the wrist in neutral.

Visual estimation: At the start of the experiment, both examiners visually estimated the pronation and supination range of the traumatised arm, blinded for the results of the other examiner (Figures 1 and 2). The visual estimation was not repeated because we anticipated that the examiner would remember the score on the first measurement.



Figure 1. *Visual estimation of supination in a 15-year-old girl with impairments of her left arm after a united forearm fracture.*



Figure 2. *Visual estimation of pronation.*

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Goniometer measurement: We used a 180-degree protractor goniometer with 2 movable arms of 30 cm, constructed of clear, flexible plastic (Figures 3 and 4). One arm of the goniometer was lined up parallel to the upper arm of the patient, the other arm was placed parallel to the distal third of the forearm. The goniometer was blocked on the front-side in order to blind the examiners during the measurement. Both examiners performed 3 independent measurements of full pronation and supination, to determine the interrater reliability. To obtain intrarater reliability, the first observer repeated the same three measurements a second time. All measurements were marked on separate forms to blind the examiners from previous results. The examiners were graduate students of the faculty of Human Movement Sciences at the VU University in Amsterdam. They were trained in measuring pronation and supination in a paediatric population by the first author.



Figure 3. *Measurement of supination with a conventional goniometer (not blinded).*

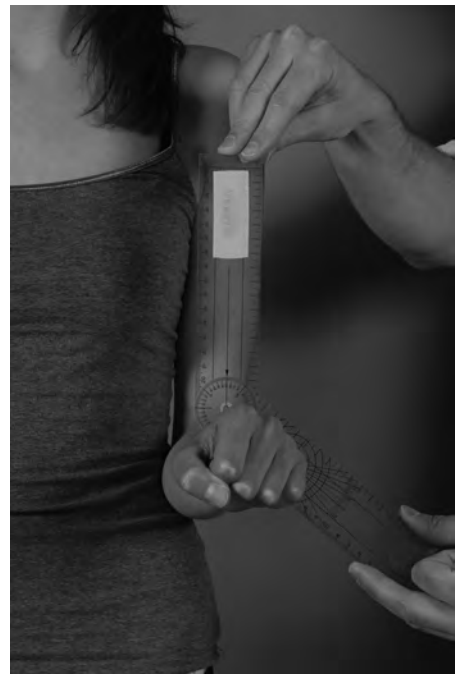


Figure 4. *Measurement of pronation with a conventional goniometer (not blinded).*

Statistical analysis

First, the results of the 3 measurements of each examination were averaged. Using SPSS 13.0, ICCs were calculated. When assessing reliability, a distinction between intra-observer and inter-observer reliability was made. Intra-observer reliability investigates the capability of one tester to produce consistent results. Inter-observer reliability examines the extent of concurrence between the results of different observers.

In addition to the ICC, the smallest detectable difference (SDD) were calculated (10). The SDD is specifically valuable for clinical use since this index allows distinguishing between measurement error and a real (treatment) change in individual measurements since only a difference between consecutive measurements that exceeds the SDD can be considered a real change. For example, a SDD of 5 degrees indicates that a follow-up measurement should differ by at least 5 degrees from a baseline measurement to be sure that there is a real change in pronation or supination angle of an individual subject. Hence, the SDD value reflects the smallest clinically detectable change. Paired t-tests were used to compare the 2 experimental methods. The effect of age on the measurement results was addressed by analysis of variance (ANOVA) with Bonferoni post-hoc comparisons. The level of significance was set at $p < 0.05$.

RESULTS

Forty-seven children (34 boys and 13 girls) were included in this study. The mean age was 11.1 ± 3.1 years (range 6-16 years). The dominant arm was fractured in 19 children. All 47 children successfully completed the study protocol. The results of the visual estimation and goniometrical measurements are demonstrated in Table 1, presenting the data of the whole group (6-16 years) and the data stratified according to the 3 age groups: 6-9 years (15 patients), 10-13 years (16 patients) and 14-16 years (16 patients). Visual estimation showed higher pronation, supination and total range of motion (ROM) angles compared to the goniometer data in all age groups. In the overall group, this difference was statistically significant for the total ROM only. For the 6-9 year old children, visual estimation angles were significantly larger than goniometer angles for supination and total ROM.

Table 1. Means, standard deviation (SD), minimum and maximum for pronation, supination and total range of motion (ROM) in degrees. The table compares the outcomes of the goniometer measurement (left) with those of the visual estimation (right). Age is in years. * indicates significant difference between the mean goniometer and mean visual estimation data.

	Age	Goniometer				Visual estimation			
		Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
Pronation	6-16	71	10	25	88	73	19	33	90
	6-9	74	6	62	87	78	15	45	90
	10-13	69	14	25	87	73	21	33	90
	14-16	69	7	60	88	69	20	38	90
Supination	6-16	85	9	64	111	87	11	50	113
	6-9	86	10	67	111	90 *	8	78	113
	10-13	87	8	64	100	86	12	53	98
	14-16	83	8	64	92	86	13	50	98
ROM	6-16	156	13	119	188	160 *	24	90	200
	6-9	160	11	136	188	168*	17	123	200
	10-13	156	15	119	172	158	25	103	180
	14-16	152	12	127	172	156	28	90	183

The interrater reliability of both methods is illustrated in Table 2. In the overall group, the goniometer method had ICCs ranging from 0.84 to 0.89, while visual estimation had slightly lower ICCs, ranging from 0.75 to 0.88. Except for two subgroup comparisons, the ICCs of the goniometer method were higher than those of visual estimation, suggesting a better interrater reliability of the goniometer method. In addition, the overall goniometer data consistently showed lower SDD values as compared to the visual estimation data (SDD: 10-15° vs 16-24°), also indicating better reliability for the goniometer method. When comparing the different age groups for the goniometer data, the eldest children consistently showed the lowest SDD scores. We did not find the same effect for visual estimation, where the youngest age group showed the lowest SDD scores. Subgroup analysis of the ICCs did not show a clear age effect.

Table 2. *Interrater reliability values per age group and measurement method. SDD = smallest detectable difference, ICC = intraclass correlation coefficient. Age is in years and SDD is in degrees.*

Measurement	Age	Goniometer		Visual estimation	
		SDD	ICC	SDD	ICC
Pronation	6-16	10	0.89	23	0.82
	6-9	10	0.65	20	0.78
	10-13	12	0.92	22	0.87
	14-16	7	0.89	28	0.77
Supination	6-16	10	0.84	16	0.75
	6-9	7	0.93	7	0.89
	10-13	15	0.63	20	0.70
	14-16	5	0.96	17	0.78
Range of motion	6-16	15	0.85	24	0.88
	6-9	11	0.89	18	0.88
	10-13	19	0.85	20	0.92
	14-16	7	0.88	34	0.83

The intrarater reliability of the goniometer method is illustrated in Table 3. In the overall group, intrarater ICCs ranged from 0.92 to 0.94 with SDDs ranging from 6 to 10° respectively. Compared to the interrater reliability, the intrarater reliability (ICC 0.92-0.94) was consistently higher (see Table 2). Furthermore, the intrarater SDDs (6-10°) were lower than the interrater SDDs (10-15°).

Table 3. *Intrarater reliability values of conventional goniometry, stratified according to age group. SDD = smallest detectable difference, ICC = intraclass correlation coefficient. Age is in years, SDD is in degrees.*

	Goniometer measurement		
	Age	SDD	ICC
Pronation	6-16	7	0.94
	6-9	9	0.73
	10-13	7	0.97
	14-16	4	0.96
Supination	6-16	6	0.93
	6-9	5	0.97
	10-13	9	0.80
	14-16	5	0.96
Range of Motion	6-16	10	0.92
	6-9	8	0.94
	10-13	14	0.90
	14-16	7	0.93

DISCUSSION

The aim of this study was to determine the intra- and interrater reliability of visual estimation and conventional goniometry for measuring forearm pronation and supination in a paediatric population with a united both-bone forearm fracture. Regarding the interrater reliability, the present results demonstrated a fair to excellent reliability for both visual estimation and goniometer measurements (ICCs 0.75 to

0.89). These results are similar to previous studies with ICCs ranging from 0.72 to 0.98, using more complex devices to measure forearm rotation^{4,5,7,9}. In this study, we found that the goniometer measurements had significantly higher ICCs and lower SDDs as compared to visual estimation, indicating better overall reliability and higher specificity. This difference may partly be explained by the higher specificity of the goniometer (1-degree steps) as compared to visual estimation (5-degree steps). To our knowledge, the only study that has dealt with visual estimation dates back to 1976 and concluded that goniometer measurements were more reliable than estimation of elbow flexion and wrist extension¹². When analysing the effect of age on the reliability of measuring forearm rotation, we found no consistent effect of age on the ICCs. However, the SDD values of the goniometer method were consistently lower in the eldest children. This indicates that the differences between repeated measures are smaller in older children. For visual estimation the opposite was found: SDD values of visual estimation were lowest in the youngest children. However, visual estimation was still less accurate as compared to goniometer measurements in the younger aged. The intrarater reliability of the goniometer measurements in the present study was excellent, ranged between 0.92 to 0.94, which is comparable with the intrarater reliability that has previously been found using more complex devices, ranging from 0.78 to 0.99^{4,6,9}. The intrarater reliability in the present study was consistently higher than interrater reliability, indicating that repeated examination by the same professional should generally be preferred.

A limitation of this study is that we compared only two examiners, both of whom were graduate students without extensive clinical experience in working with this paediatric population. It should be noted, however, that previous literature showed that the accuracy of measurements is independently of the type of professional⁴. Another limitation was that the intrarater reliability of visual estimation could not be reliably tested in the current study design, which consisted of a one day visit of the children. The particular strengths of this study included the blinded design, the measurement of a relevant group of patients and the use of conventional goniometry as well as visual estimation as primary methods. Furthermore, the evaluation of the intra- and inter reliability, as well as use of smallest detectable difference scores, gives it substantial clinical relevance. In conclusion, based on the present study, we recommend the use of the conventional goniometer for measuring

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pronation and supination in daily practice. If an uncooperative child interferes with the measurement, visual estimation is a good second choice. To minimise the variability of the measurements, professionals should measure the forearm rotation with the arms in the same documented position.

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CHAPTER 9

Which factors affect limitation of pronation/supination after forearm fractures in children? A prospective multicentre study

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Colaris JW, Allema JH, Reijman M, de Vries MR, Ulas Biter L, Bloem RM, van de Ven CP, Verhaar JA.

ABSTRACT

Introduction: Both-bone forearm fractures in children frequently result in a limitation of pronation/supination, which hinders daily activities. The purpose of this prospective multicentre study was to investigate which clinical factors are related to the limitation of pronation/supination in children with a both-bone forearm fracture.

Methods: In four Dutch hospitals consecutive children (<16 years) who sustained a both-bone forearm fracture were included. Children were followed for 6-9 months and data from questionnaires, physical examination, and X-rays were collected. Univariate and multivariate logistic regression analyses were used to assess the relationship between limitation of pronation/supination (≥ 20 degrees) and several clinical factors.

Results: A group of 410 children with both-bone forearm fractures were included of which 10 children missed the final examination (follow-up rate of 97.6%). We found that a re-fracture (odds ratio (OR) 11.7, 95% confidence interval (CI) 1.2; 118.5), a fracture in the diaphysis (OR 3.3, 95% CI 1.4; 7.9) and less physiotherapy during follow-up (OR 0.9, 95% CI 0.82; 0.98) were independently associated with a limitation of pronation/supination of 20 degrees or more.

Conclusions: These findings imply that a re-fracture and a diaphyseal located fracture were independently of each other associated with a limitation of pronation/supination in children with a both-bone forearm fracture. Furthermore, in children with severe limitation extensive physiotherapy is associated with better functional outcome.

INTRODUCTION

Severe limitation of pronation/supination following both-bone forearm fractures in children hinders daily activities. For example, while pronation is used for writing and typing, movements such as perineal hygiene and accepting monetary change require supination. Fortunately, the ipsilateral shoulder can compensate mild limitation of pronation by abduction and internal rotation, and mild limitation of supination by adduction and external rotation.

Pronation/supination of the forearm is not a simple rotational motion but a complex motion with rotation and translation¹. This complex motion in combination with the complex anatomy of the forearm makes it difficult to find the exact cause of this limitation. In general, it can be caused by pathology of the bones or soft tissue around it. Pathology of the bones consists of a malunion of the radius and/or ulna and is a well-known cause of limitation of pronation/supination²⁻⁹. The soft-tissue pathology as cause of limitation is less well known. Some studies reported on contractures of the interosseous membrane^{10,11} while others stressed the role of contractures around wrist and elbow^{12,13}.

Although previous literature has reported on pathology of bones and soft tissue as a cause of limitation of pronation/supination, many other clinical factors associated with this limitation have not yet been explored. However, knowledge on these factors can contribute to better clinical care by change of treatment (when required) and detailed information provided to parents and children.

Therefore, we designed a prospective multicentre study with the purpose of investigating which clinical factors are related to the limitation of pronation/supination in children with a both-bone forearm fracture.

MATERIALS AND METHODS

Study design and participants

This prospective study included consecutive children with a forearm fracture of radius and ulna 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 Sint Franciscus Hospital (Rotterdam). The

regional medical ethics committee approved the study. Informed consent for participation was obtained from all parents and from all children aged ≥ 12 years.

We included children aged < 16 years who sustained a both-bone forearm fracture in the diaphysis or distal metaphysis. The criteria for reduction were a priori defined and based on previous studies¹⁴⁻²³ (Table 1). Exclusion criteria were torus fractures of both radius and ulna, fractures older than 1 week, severe open fractures (Gustilo II and III)²⁴ and re-fractures.

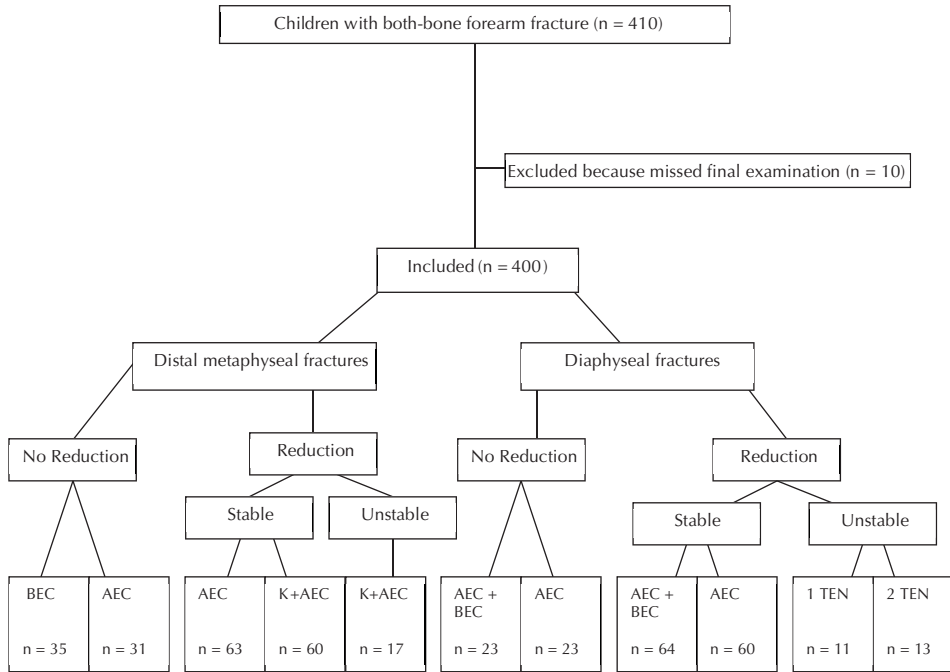
Table 1. *Criteria for reduction of the fracture of radius and/or ulna based on posteroanterior and/or lateral radiographs.*

Type of deformity	Age in years	Deformity
Angulation	< 10	> 15 degrees
	10-16	> 10 degrees
Translation	< 16	$>$ half of bone diameter
Rotation	< 16	> 0

Procedures

The included children participated in several randomised controlled studies. The study protocol distinguished different types of both-bone forearm fractures (Table 2). Briefly, distal metaphyseal fractures without need for reduction were treated with below-elbow cast (BEC) or above-elbow cast (AEC) for 4 weeks²⁵, while distal metaphyseal fractures with reduction were treated with or without Kirschner wires (K wires) in combination with AEC for 4 weeks²⁶. In addition, diaphyseal fractures without reduction and reduced stable diaphyseal fractures were treated for 6 weeks AEC, or a combination of 3 weeks AEC and 3 weeks BEC. Finally, unstable diaphyseal fractures were fixated with 1 or 2 intramedullary nails in combination with 3 weeks AEC. In case of an AEC, the elbow was set in 90 degrees of flexion with the forearm in neutral position. A BEC allowed free movement of the elbow joint.

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n = number of children; BEC = below elbow cast; AEC = above elbow cast;
 K = Kirschner wires; TEN = Titanium Elastic Nail.

Table 2. Flowchart of enrolment in the study

All children were clinically and radiographically evaluated during the first 6 weeks after trauma by a surgeon. Fracture displacement during follow-up, as defined by the loss of reduction according to the primary reduction criteria (Table 1), required new fracture reduction. Finally, the cast and transcutaneous hardware were removed in the plaster room, while buried hardware was removed in the operating room.

One orthopaedic surgeon, who was not involved in primary treatment, examined all children 2 and 6 months after trauma. Only the children with unstable diaphyseal fractures were examined 2 and 9 months after initial trauma because intramedullary nails were removed at 8 months after trauma. During both examinations, the orthopaedic surgeon measured pronation/supination of both arms.

This technique was standardised with the use of a 180° goniometer constructed of clear, flexible plastic with 2 movable arms of 30 cm²⁷. Children who suffered from at least 30 degree of limitation at the 2-month examination were referred to a physiotherapist.

Radiographs were taken directly after trauma, after reduction, during the treatment in cast, and at final follow-up. The orthopaedic surgeon measured angulation, translation, rotation and shortening of all fractures to determine primary displacement, displacement during treatment with cast, and final displacement. Rotation was detected by differences in diameter of diaphysis of ulna and radius on lateral and posteroanterior radiographs²⁸. To assess the interrater reproducibility of the radiological assessment, a trauma surgeon who was not involved in treatment, re-measured the angulation of the fracture in 45 children independently of the orthopaedic surgeon.

Multivariate analysis

Our dependent variable was limitation of pronation/supination of 20 degrees or more at the end of follow-up. For the following factors we assessed whether they were related to the above-mentioned dependent variable: age at time of fracture, dominant arm fractured, location of the fracture (diaphysis vs. distal metaphysis), type of fracture (torus, greenstick, complete), primary displacement of the fracture, number of reductions, presence of a re-fracture, duration of AEC, number of physiotherapy visits, and final displacement of the fracture.

This choice of factors was based on the assumption that less limitation would be found in children of younger age because of their higher repair capacity⁷. Furthermore, less limitation was expected as the fracture occurred in the dominant arm due to the need for the dominant arm in daily activities. The assumption of less limitation in distal metaphyseal fractures, less severe type of fractures, less primary displacement of the fracture, fewer reductions and no re-fracture, is in all these cases based on less soft tissue damage^{6,7,29}. Thereby, we postulated that short immobilisation of the elbow in AEC and frequent visits to a physiotherapist might cause less limitation³⁰. The effect of malunion on limitation has been mentioned by others²⁻⁹.

Statistical Analysis

To assess which factors were related to limitation of pronation/supination of 20 degrees or more at the end of follow-up, multivariate logistic regression analysis (via the 'enter' method) was used to calculate odds ratios (ORs) and 95% confidence intervals (95% CI). In all analyses, a two-sided p-value of ≤ 0.05 was considered significant. Statistical analyses were performed with SPSS 17.0 (SPSS Inc., Chicago, USA).

RESULTS

Between January 2006 and August 2010 a total of 410 children with both-bone forearm fractures were included. Ten children missed the final examination and were therefore excluded (follow-up rate of 97.6%). The included children had several types of both-bone forearm fractures (Table 2). The mean length of follow-up was 218 (± 49) days.

Table 3 presents the results of both groups and of the univariate and multivariate analyses. Six of 10 factors had a significant univariate relationship with limitation of pronation/supination. Half of these factors also showed a significant multivariate relationship and therefore had an independent relation with limitation of pronation/supination.

The presence of a re-fracture was strongly associated with limitation of pronation/supination (Figure 1) with an OR of 11.7 (95% CI 1.2; 118.5). Thereby, the location of the fracture (diaphyseal vs. distal metaphyseal) and number of physiotherapy visits were significant in the multivariate analyses with an OR of 3.3 (95% CI 1.4; 7.9) and 0.90 (95% CI 0.82; 0.98), respectively. These findings imply that a re-fracture, a diaphyseal located fracture and less physiotherapy were independently of each other associated with a limitation of pronation/supination of 20 degrees or more in children with a both-bone forearm fracture. The OR of 11.7 for a re-fracture implies that a child who sustained a re-fracture had an almost 12 times increased risk to end up with a limitation of pronation/supination of 20 degrees or more.

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Table 3. Factors associated with limitation of pronation/supination.

	Logistic regression analyses			
	No limitation	Limitation	Univariate OR (95% CI)	Multivariate OR (95% CI)
Age at time of fracture, years	7.7 ± 3.4	8.9 ± 3.6	1.1 (1.0; 1.2)	-
Dominant arm fractured, %	39.4	40.7	-	-
Location of fracture, %			2.7 (1.7; 4.2)	3.3 (1.4; 7.9)
Distal metaphyseal	57.9	33.9		
Diaphyseal	42.1	66.1		
Type of fracture radius, %			-	-
Torus	1.4	0.9		
Greenstick	44.4	49.1		
Complete	54.2	50.0		
Type of fracture ulna, %			-	-
Torus	5.2	8.3		
Greenstick	54.2	59.3		
Complete	40.6	32.4		
Primary deformity of fracture				
Angulation, degrees	24.2 ± 14.4	24.3 ± 12.4	-	-
Translation, % of width	37.6 ± 44.4	27.9 ± 41.2	-	-
Rotation, %	9.4	9.3	-	-
Shortening, %	35.2	25.9	-	-
Number of reductions, %			-	-
0	27.0	20.2		
1	67.2	67.9		
2	5.5	11.0		
3	0.3	0.9		
Presence of a re-fracture, %	1.0	12.8	14.1 (4.0; 50.1)	11.7 (1.2; 118.5)
Days in above-elbow cast	29.4 ± 8.6	32.7 ± 12.1	1.0 (1.0; 1.1)	-
Number of physiotherapy visits	7.5 ± 7.5	4.3 ± 4.1	0.9 (0.8; 1.0)	0.90 (0.82; 0.98)
Final deformity of fracture				
Angulation, degrees	9.3 ± 4.4	8.3 ± 4.1	1.0 (0.9; 1.0)	-
Translation, % of width	6.8 ± 13.1	4.9 ± 9.2	-	-

Limitation is defined as limitation of pronation and supination of 20 degrees or more; % = percentage; Values are presented as mean ± standard deviation unless stated otherwise; OR = Odds Ratio; CI = Confidence Interval. In the table of odds ratio only the significant results are mentioned.



Figure 1. *Child with a limitation of supination of her left arm after a both-bone forearm fracture*

DISCUSSION

The purpose of this prospective multicentre study was to investigate which clinical factors are related to the limitation of pronation/supination in children with a both-bone forearm fracture. The results suggest an increased risk of limitation of pronation/supination of 20 degrees or more in case of a re-fracture and a fracture localised in the diaphysis. Furthermore, an increased risk was found in children with a limitation of >30 degrees at the 2-month examination who had received less physiotherapy.

The strong relationship between re-fractures and limitation might be explained by additional injury to the forearm that was still recovering from the primary fracture. Repeated immobilisation in cast might have resulted in more severe contractures with a higher limitation of pronation/supination. The influence of diaphyseal fractures on limitation can be explained by the great amount of energy necessary to fracture the thick cortex of diaphyseal bone. This high energy level may result in severe injury to the interosseous membrane, which could affect the complex motion of pronation/supination by contractures. Thereby, the benefits of physiotherapy also

suggest a role of contractures in limitation of pronation/ supination. In conclusion, our findings suggest that soft tissue injury during trauma can result in contractures resulting in limitation of pronation/supination.

Previous studies

Of all the factors we assessed to establish whether they were related to limitation of pronation/supination, several had been studied previously. Robert et al. reported on greater limitation in older children, whereas Price et al. mentioned that age had no influence^{6,7}. In our multivariate analysis age had no significant relation with limitation. Several studies support our finding that diaphyseal location of a forearm fracture has a significant relation with limitation of pronation/supination^{6,7,29}. Moreover, Webb et al. reported a better arc of elbow motion in favour of BEC compared to AEC³⁰; however, this finding was not supported by our analysis.

Previous studies most frequently discuss two main causes of limitation of pronation/supination after forearm fractures in children, namely malunion and soft tissue contractures. Nevertheless, an interaction between these two causes can occur when a malunion changes the tension of the interosseous membrane^{5,9,13,31}.

Malunion as cause of limitation of pronation/supination after forearm fractures is often reported and consists of malalignment in angulation, translation or rotation^{2-9,29}. Angular malalignment of ≥ 20 degrees may result in significant limitation, as described earlier^{2,5}. Thereby, malunions with malalignment in translation resulted in limitation of pronation/supination by the loss of radial bow or impingement between the forearm bones^{7-9,29}. Furthermore, in cadaver studies, rotational malalignment of ulna and radius in the opposite direction caused the greatest limitation^{3,4,8}. In contrast with these studies, we found no significant relation between malunion and limitation in our multivariate analysis.

In line with our findings, others also reported that malunion was not a cause of limitation of pronation/supination^{6,31-36}. Some found a poor correlation between residual angular malunion and the final range of pronation/supination⁶. Others stated that perfect anatomical fracture alignment did not always result in complete restoration of pronation/supination^{31,34}. Thus, anatomical corrective osteotomies for malunited forearm fractures did not always resolve the limitation of pronation/supination^{35,36}.

Furthermore, several studies support the important role of contractures of soft tissue in limitation of pronation/supination after forearm fractures^{7,10-13}. Some reported on contractures of the interosseous membrane^{10,11} while others described the role of contractures around wrist and elbow^{12,13}. One study described a correlation between initial fracture displacement, MR-detected interosseous membrane alternations, and limitation of pronation/supination³⁷.

In summary, previous studies have conflicting opinions about the role of malunion in the limitation of pronation/supination after forearm fractures in children. We found a significant role of malunion based on univariate analysis. In contrast, no significant role was found in our multivariate logistic regression analysis, suggesting that malunion is not independently associated with a limitation of pronation/supination of 20 degrees or more.

Our results suggest that scarring of the injured soft tissue around the fracture can lead to contractures that probably play an important role in limitation of pronation/supination.

Limitations

The present study has several limitations. Primarily, rotation of the fracture was detected by differences in the diameter of diaphysis of ulna and radius on lateral and posteroanterior radiographs²⁸; this technique probably overlooks subtle rotation of fractures. However, Kasten et al. found limitation of pronation/supination only in fractures with more than 30 degrees of malrotation, which should have been detected with the method used⁴.

Secondly, ideally our follow-up period should have been longer in this young population with the capacity to correct malunion by growth. Nevertheless, malunion was not independently associated with higher limitation in our multivariate analysis.

Thirdly, we cannot exclude injury to the distal or proximal radio-ulnar joint as a possible cause of limitation of pronation/supination.

Conclusion

The results of this prospective multicentre study, with an analysis of 400 children, suggest that children who suffered from a diaphyseal fracture or sustained a re-fracture have an increased risk of limitation of pronation/supination during follow-up.

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Furthermore, in children with severe limitation extensive physiotherapy is associated with better functional outcome.

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CHAPTER 10

Angular malalignment as cause of limitation of forearm rotation: *an analysis of prospectively collected data of both-bone forearm fractures in children*

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ABSTRACT

Introduction: Although limitation of pronation/supination following both-bone forearm fractures in children is often attributed to an angular malunion, no clinical study has compared pronation/supination and angular malalignment of the same child by analysis of prospectively collected clinical data. Therefore, the purpose of this trial was to explore whether limitation of pronation/supination can be predicted by the degree of angular malalignment in children who sustained a both-bone forearm fracture.

Methods: In four Dutch hospitals, consecutive children aged ≤ 16 years with a both-bone forearm fracture were prospectively followed for 6-9 months. At final follow-up, pronation/supination and angular malunion on radiographs were determined.

Results: Between January 2006 and August 2010 a total of 410 children were prospectively followed of which 393 children were included for analysis in this study. The mean age of the children was 8.0 (± 3.5) years, 63% was male and 40% fractured their dominant arm. The mean time to final examination was 219 (± 51) days. Children with a metaphyseal both-bone fracture of the distal forearm with an angular malalignment of ≤ 15 degrees had a 9-13% chance to develop a clinically relevant limitation (i.e. < 50 degrees of pronation and/or supination), while children with an angular malalignment of ≥ 16 degrees had a 60% chance. Children with diaphyseal both-bone forearm fractures with ≤ 5 degrees of angular malalignment had a 13% chance to develop a clinically relevant limitation, which showed no significant increase with a further increase of angular malalignment.

Conclusions: Children who sustained a both-bone forearm fracture localized in the distal metaphysis have a higher chance to develop a clinically relevant limitation of forearm rotation in case of a more severe angular malalignment, while children with a diaphyseal both-bone forearm fracture had a moderate chance of limitation, irrespective of the severity of the angular malalignment.

INTRODUCTION

Both-bone forearm fractures in children might result in a limitation of forearm rotation that only affects daily activities if pronation and/or supination is ≤ 50 degrees¹. This limitation is often attributed to an angular malunion as a result of neglected primary or secondary fracture displacement. In case of a displaced fracture in a child, the remodelling capacity of the growing bone often confronts the clinician with a dilemma regarding treatment, i.e. whether to perform a reduction of the fracture, or to accept some degree of displacement with possibly less favourable cosmetic and functional results.

Studies of artificially created deformities in human upper-extremity cadaver specimens indicated that angular deformities of the forearm of 10 degrees or less resulted in minimum limitation of pronation/supination, while 20 degrees of angulation caused an important loss^{2,3}. Others compared these experimental results with data obtained from clinical and radiographic examination and found that the experimental results predicted the clinical loss of pronation and supination relatively well⁴.

Although these findings are highly relevant for the clinician's decision-making process, no clinical study has compared pronation/supination and angular malalignment of the same child by analysis of prospectively collected clinical data. Therefore, the purpose of this trial was to explore whether limitation of pronation/supination can be predicted by the degree of angular malalignment in children who sustained a both-bone forearm fracture.

MATERIALS AND METHODS

Study design and participants

A prospective study was performed on all consecutive children with a forearm fracture of radius and ulna who visited the emergency department of one of four participating hospitals. The Dutch hospitals that participated were Erasmus Medical Center (Rotterdam), Haga Hospital (The Hague), Reinier de Graaf Hospital (Delft) and Sint Franciscus Hospital (Rotterdam). The regional medical ethics committee approved the study. Informed consent was obtained for participation by all parents and all children aged ≥ 12 years.

Included in the study were children aged ≤ 16 years who sustained a both-bone forearm fracture in diaphysis or distal metaphysis. The criteria for reduction were *a priori* defined and based on previous studies⁵⁻¹⁴ (Table 1). Exclusion criteria were torus fractures of both radius and ulna, fractures older than 1 week, severe open fractures (Gustilo II and III)¹⁵, re-fractures, and children lost to follow-up.

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

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

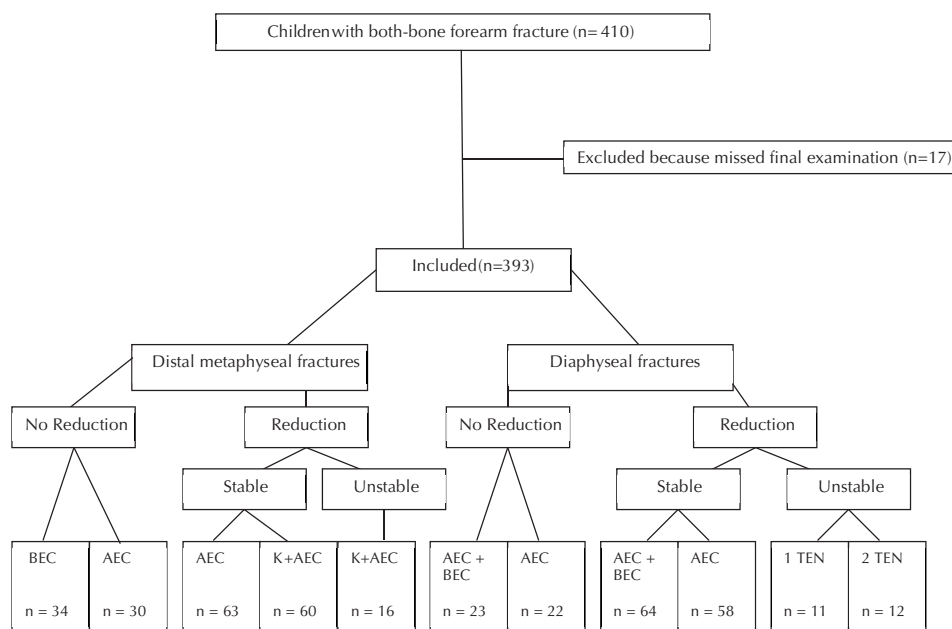
Procedures

The included children participated in several randomized controlled studies. The study protocol distinguished between different types of both-bone forearm fractures (Table 2). The separate studies are described in detail in previous publications^{16,17}. Briefly, distal metaphyseal fractures without need for reduction were treated with below or above-elbow cast for 4 weeks, while distal metaphyseal fractures with reduction were treated with or without Kirschner wires in combination with above-elbow cast for 4 weeks. Furthermore, diaphyseal fractures without reduction and reduced stable diaphyseal fractures were treated with 6 weeks above-elbow cast, or a combination of 3 weeks above-elbow cast and 3 weeks below-elbow cast. Finally, unstable diaphyseal fractures were fixated with 1 or 2 intramedullary nails in combination with 3 weeks above-elbow cast.

An orthopaedic surgeon (not involved in treatment) examined all children at 2 and 6 months after initial trauma using a standardized technique to measure flexion and extension of wrist and elbow in combination with pronation and supination of both arms¹⁸. Final radiographs were made 6 months after the initial trauma. Only the children who were treated with intramedullary nails had a final examination and

final radiographs at 9 months. All children with at least 30 degrees of functional impairment (combined functional impairment of pronation/supination and flexion/extension of wrist/elbow) at the 2-months examination were referred to a physiotherapist. A clinically relevant limitation of forearm rotation was defined as pronation and/or supination of ≤ 50 degrees in the injured forearm¹.

Table 2. Flowchart of enrolment in the study



n = number of children; BEC = below elbow cast; AEC = above elbow cast;

K = Kirschner wires; TEN = Titanium Elastic Nail

Radiographic analysis

Angulation of radius and ulna was measured on final posteroanterior and lateral radiographs (at 6-9 months) to determine angular malalignment by one orthopaedic surgeon (not involved in treatment). The maximum angular malalignment of radius or ulna on either the posteroanterior or lateral radiograph was used for the analysis. To assess the inter-rater reproducibility of the radiological assessment, a trauma surgeon (not involved in treatment) re-measured the angulation of the fracture in 45 children.

Statistical analysis

First, 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 and range.

The main study items (limitation of pronation/supination of the fractured arm ≤ 50 degrees as dependent variable and degree of angular malalignment as independent variable) were analysed using logistic regression analysis. If necessary, adjustments were made for unbalanced covariates. Statistical analyses were performed with the SPSS version 17.0 (SPSS Inc., Chicago, USA).

RESULTS

Between January 2006 and August 2010 a total of 410 children were prospectively followed in four Dutch hospitals; of these, 393 children were included for analysis in the present study (Table 2). The excluded children had either no clinical and/or no radiological examination at the end of follow-up. The mean time to final examination was 219 (99-440) days. The mean age of the children was 8.0 (0-16) years. The children were divided in two groups in accordance with their limitation of forearm rotation, i.e. more or less than 50 degrees of impairment. Table 3 presents the baseline characteristics of the total study population and per group. There was a significant difference between the two groups in location of fracture, and type of fracture of both the radius and ulna; therefore, the statistical analyses were corrected for these baseline variables.

Table 4 presents different categories of maximum angular malalignment on final radiographs in relation to clinically relevant limitation of forearm rotation at final clinical examination, i.e. < 50 degrees of pronation and/or supination. Overall 86 children had a malunion of ≤ 5 degrees of which 9.3% showed a clinically relevant limitation of forearm rotation at final follow-up. The most severe malunion groups (11-15 and >16 degrees of malunion) had significantly more children with a clinically relevant limitation of forearm rotation ($p < 0.0001$).

Table 5 presents the limitation of forearm rotation in correlation with the severity of malunion and location of the fracture (distal metaphyseal/diaphyseal). A significantly higher percentage of children with a clinically relevant limitation of forearm rotation

Table 3. *Baseline characteristics of the study population.*

	Total	pronation/supination	
		< 50 degrees	> 50 degrees
Number	393	80	313
Age in years at time of fracture: mean (range)	8.0 (0-16)	8.1 (3-15)	8.0 (0-16)
Gender, % male	63	69	61
Dominant arm fractured, %	40	34	41
Follow-up in days: mean (range)	219 (99-440)	212 (143-440)	219 (99-406)
Location of fracture (%)*,			
diaphyseal	48	70	43
metaphyseal	52	30	57
Type of fracture ulna (%)**,			
torus	6	3	7
greenstick	55	42	58
complete	39	55	35
Type of fracture radius (%)***,			
torus	1	0	2
greenstick	45	35	47
complete	54	65	51

Significant differences between the two groups in location of fracture (* $p < 0.0001$), type of fracture ulna (** $p = 0.004$) and type of fracture radius (***) $p = 0.038$)

was found only in the distal metaphyseal localized fractures with >16 degrees of malunion ($p < 0.0001$). Furthermore, the significant differences found between the two groups were similar with and without adjustment for unbalanced covariates.

Chapter 10

Table 4. *Angular malunion in relation to clinical relevant limitation of pronation and/or supination.*

Maximum angular malunion, degrees	< 50 degrees of pronation and/or supination, % (ratio)
0-5	9.3 (8/86) ^{1,2}
6-10	15.6 (28/179)
11-15	31.9 (30/94) ¹
>16	41.2 (14/34) ²

^{1,2} : Significant differences between two groups ($p < 0.0001$), with and without adjustment for location of fracture, and type of fracture of ulna and radius.

Table 5. *Angular malunion in relation to clinically relevant limitation of pronation/supination with differentiation between fracture location.*

Maximum angular malunion: degrees	< 50 degrees of pronation and/or supination: % (ratio)	
	Distal metaphysis	Diaphysis
0-5	8.5 (6/71) ¹	13.3 (2/15)
6-10	9.0 (9/100)	24.1 (19/79)
11-15	13.0 (3/23)	38.0 (27/71)
>16	60.0 (6/10) ¹	33.3 (8/24)

¹ Significant difference between the two groups ($p < 0.0001$), with and without adjustment for location of fracture, and type of fracture of ulna and radius.

DISCUSSION

This study shows that children who sustained a both-bone forearm fracture localized in the distal metaphysis have a high chance (60%) to develop a clinically relevant limitation of forearm rotation in case of a more severe angular malalignment (>16 degrees), while children with a diaphyseal both-bone forearm fracture have a moderate chance of limitation (13-33%) irrespective of the severity of the angular malalignment.

Fractures of the distal metaphysis are localized close to the most active distal growth plate of the forearm, which makes remodelling by growth more likely than

fractures in the diaphysis. Therefore, a distal metaphyseal fracture with a mild to moderate angular displacement (≤ 15 degrees) does not always need to be reduced, especially in younger children with a high potential for remodelling by growth. In contrast, clinicians should remain alert regarding children with diaphyseal fractures, because even mild angular malalignment resulted in a clinically relevant limitation of forearm rotation. Because diaphyseal fractures showed no significant increase in limitation of pronation/supination in more severe angular malalignment fractures, contractures of the injured interosseous membrane might also play a role.

Previous studies

Malunion as cause of limitation of pronation/supination after forearm fractures is often reported and might consist of malalignment in angulation, translation or rotation^{2,19-26}.

Two studies of artificially created deformities in human upper-extremity cadaver specimens indicated that angular deformities of the forearm of 10 degrees or less resulted in minimum limitation of pronation/supination, whereas 20 degrees of angulation caused an important loss of forearm rotation^{2,3}. These findings are supported by our study only in distal metaphyseal fractures, whereas many diaphyseal fractures even showed a limitation in minor angular malalignment. Moreover, previous studies mentioned that angular malalignment in diaphyseal fractures more often resulted in limitation of pronation/supination than similar angular malalignment in metaphyseal fractures^{2,3}. This finding was confirmed in our study with up to 16 degrees of angular malalignment.

Malalignment in translation is reported to be a cause of limitation of pronation/supination by the loss of radial bow or impingement between the forearm bones^{22,24-26}. In the present study the primary translational displacement of the fracture was changed by appositional periosteal bone formation and at final follow-up only minimal callus without notable translational malalignment was seen on the radiographs. This made us believe that malalignment in translation did not significantly contribute to limitation of forearm rotation.

One cadaveric study described that rotational malalignment might result in limitation of pronation/supination, especially if the rotational malalignment of the ulna and radius was in the opposite direction. In our clinical study the final radiographs did not show any rotational malalignment.

Study limitations

In the analysis based on differentiation of fracture location, because the number of included children was relatively small these results should be interpreted with caution. Furthermore, the impairment of forearm rotation might hinder a perfect positioning of the forearm during radiography, which might influence measurement of the angular malalignment. In this way, subtle rotational malalignment might contribute to the limitation of forearm rotation and is difficult to measure on a conventional radiograph. Thereby the present study focused only on limitations related to malalignments, while contractures of traumatized soft tissue and pathology in the distal or proximal radio ulnar joint may also have played a role. The final limitation is the relatively short follow-up, as there is a remodelling of malunions by growth in children which possible influences the forearm rotation.

Conclusion

This study shows that children who sustained a both-bone forearm fracture localized in the distal metaphysis have a high chance to develop a clinically relevant limitation of forearm rotation in the case of more severe angular malalignment, while children with a diaphyseal both-bone forearm fracture have a moderate chance of limitation irrespective of the severity of the angular malalignment.

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CHAPTER 11

Three-dimensional imaging of children with severe limitation of pronation/supination after a both-bone forearm fracture

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ABSTRACT

Introduction: Although both-bone forearm fractures in children may result in severe limitation of forearm rotation, finding the cause remains a diagnostic challenge. This study tries to evaluate the role of rotational malunion, bony impingement and contractures of the interosseous membrane.

Patients and methods: Children (5-16 years) who suffered from a both-bone forearm fracture in diaphysis or distal metaphysis with a limitation of pronation/supination ≥ 40 degrees at ≥ 6 months after trauma were included for analysis with conventional radiographs, computed tomography (CT) and magnetic resonance imaging (MRI).

Results: A total of 410 children with a both-bone forearm fracture were prospectively followed in four Dutch hospitals. At a median of 205 days, 7.3% suffered from a limitation of pronation/supination ≥ 40 degrees. 14 children were included (median limitation of 40 degrees) and the radiographs revealed a median maximum angular malunion of 16 degrees. CT analysis showed rotational malunion of both radius (median 19 degrees) and ulna (median 9 degrees). MRI analysis revealed neither bony impingement nor contractures of the interosseous membrane.

Conclusions: Three-dimensional imaging of children with a severe limitation of pronation/supination after a both-bone forearm fracture revealed rotational malunions of both radius and ulna without bony impingement or soft tissue contractures.

INTRODUCTION

Both-bone forearm fractures in children generally heal without complications. While a limitation of pronation/supination of > 20 degrees has been reported in 3-30% of children after a both-bone forearm fracture, especially the severe limitations of rotation may interfere with daily activities¹⁻⁴.

Although a malunion is often mentioned as main cause of limitation of forearm rotation⁵⁻¹² there is no consensus on this. Whereas several studies described limitation without a malunion^{11,13,14}, others mentioned malunions without limitation¹⁵ or persistent limitation after a corrective osteotomy with restoration of anatomical alignment¹⁶⁻¹⁸. Other bone-related causes of limitation are a synostosis, or an impingement between radius and ulna^{9,11,19}. The exact role of soft tissue involvement in limitation of rotation remains unknown²⁰⁻²⁵. Contractures of the interosseous membrane might play a more significant role than contractures of capsules of wrist and elbow^{2,3,15}.

Unravelling the exact cause of limitation after a both-bone forearm fracture in children remains a diagnostic challenge. Therefore this study tries to evaluate the role of rotational malunion, bony impingement and contractures of the interosseous membrane by three-dimensional imaging.

MATERIALS AND METHODS

Study design and participants

A prospective study was performed including consecutive children with a forearm fracture of radius and ulna who visited the emergency department of one of four Dutch hospitals: Erasmus Medical Center (Rotterdam), Haga Hospital (The Hague), Reinier de Graaf Hospital (Delft) and Sint Franciscus Hospital (Rotterdam). The regional medical ethics committee approved the study. Informed consent was obtained from all parents and all children aged >12 years. For the present study we included children aged 5-16 years who sustained a both-bone forearm fracture in diaphysis or distal metaphysis with a limitation of pronation/supination ≥ 40 degrees at final examination (≥ 6 months after trauma) (Figure 1).

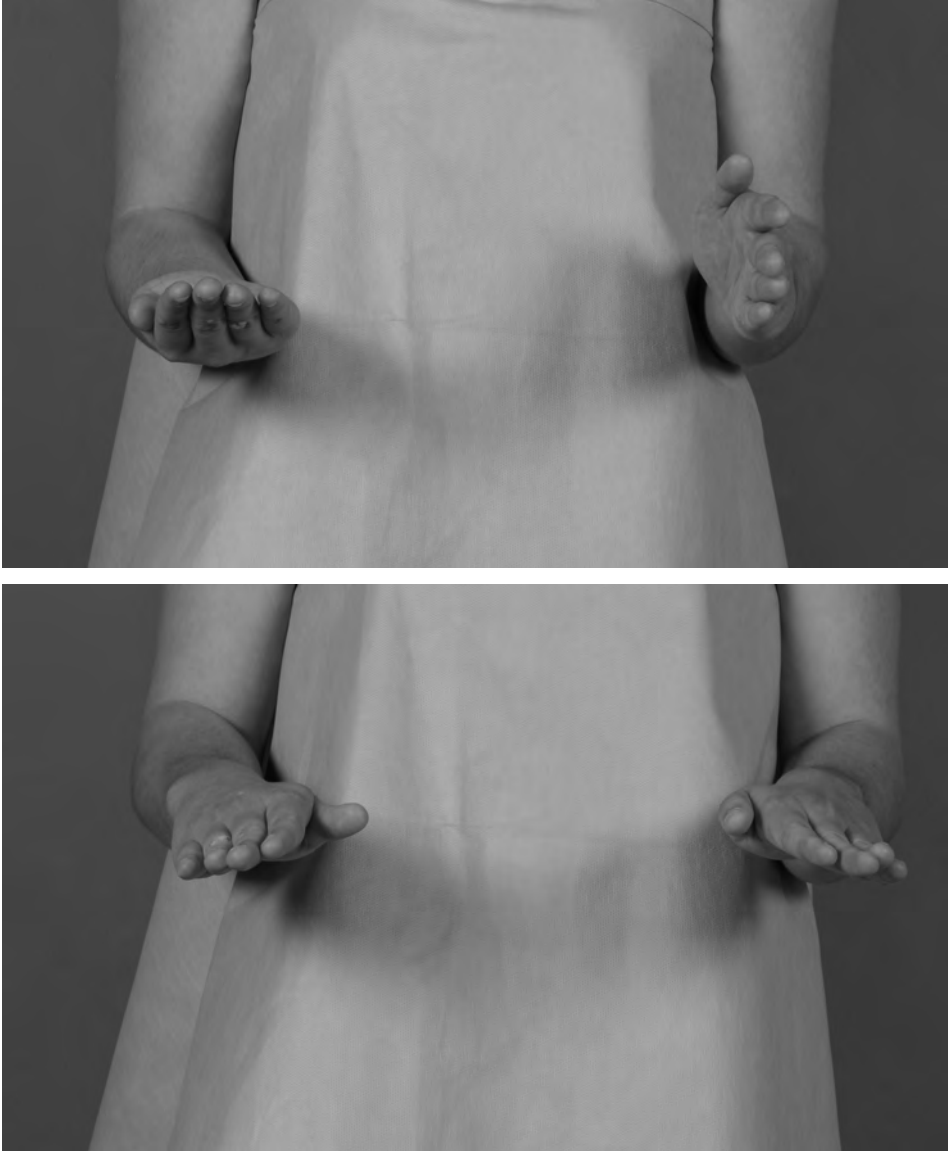


Figure 1. A severe limitation of supination after a both-bone forearm fracture.

Clinical examination

The included children were treated based on the study protocol. This protocol distinguished several types of fractures with several types of treatment. Briefly, distal metaphyseal fractures without need for reduction were treated with below-elbow or above-elbow cast for 4 weeks², while distal metaphyseal fractures with reduction were treated with or without Kirschner wires in combination with above-elbow cast for 4 weeks¹. Furthermore, diaphyseal fractures without reduction and reduced stable diaphyseal fractures were treated with 6 weeks above-elbow cast, or a combination of 3 weeks above-elbow cast and 3 weeks below-elbow cast³. Finally, unstable diaphyseal fractures were fixated with 1 or 2 intramedullary titanium nails in combination with 3 weeks above-elbow cast⁴.

One orthopaedic surgeon (who was not involved in primary treatment) measured pronation/supination of both arms two months after initial trauma. This technique was standardized with the use of a 180° goniometer constructed of clear, flexible plastic with 2 movable arms of 30 cm²⁶. Patients with at least 30 degrees of limitation 2 months after initial trauma were referred to physiotherapy.

Six to nine months after the initial trauma the orthopaedic surgeon re-measured the pronation/supination of the traumatised arm. Children with a limitation of pronation/supination of ≥ 40 degrees were asked to participate in this study.

Radiographic analysis

Conventional radiography

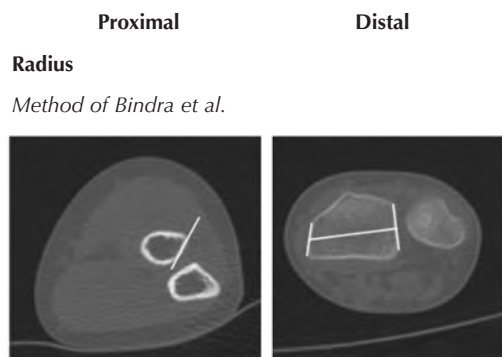
One orthopaedic surgeon measured the fracture characteristics on conventional posteroanterior and lateral radiographs directly after trauma and at final examination (6-9 months after trauma) (Table 2 and 3).

Computer tomography

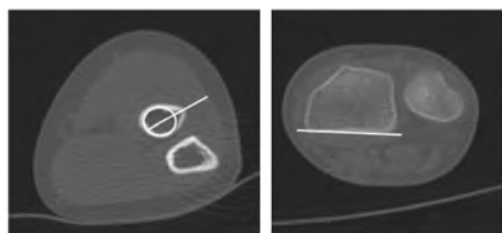
Torsion angle of the radius/ulna was defined as the angle between the proximal and distal metaphysis in the transverse plane²⁷. To compare torsion angles of left and right radius/ulna, a computed tomography (CT) scanner was used to scan elbow and wrist joints of both sides. We defined rotational malunion as a difference in torsion angles of respectively radius and ulna between the injured and uninjured arm. All images were acquired using a GE Lightspeed 4-slice CT scanner (General Electric

Healthcare; Milwaukee, WI, USA). Image acquisition parameters were a X-ray tube potential of 80 kVp, a tube current of 30 mA and 2.50-mm slice thickness. Images were reconstructed using a high spatial frequency reconstruction algorithm (Boneplus).

With the child lying prone in the scanner, both arms were placed in overhead position; the elbows were extended and the forearms were pronated so that the volar aspect of the elbow was placed flat on the table. Axial images through the maximum prominence of the bicipital tuberosity and the distal two centimetres of both radii were made simultaneously with use of a routine CT imaging protocol. This technique of scanning has shown good reproducibility²⁷. The measurements of torsion angles of radius and ulna of both arms were performed with the tools integrated in the PACS system used in our institution, i.e. iSite Radiology 3.5 (Philips Medical Systems, Best, the Netherlands). The difference in torsion angles of the radius of the traumatized arm and non-traumatized arm was calculated and defined as rotational malunion of the radius. The same procedure was repeated to determine the rotational malunion of the ulna. The orthopaedic surgeon and a senior resident of the radiology department (independently of each other) measured the torsion angle of the radius and ulna of both arms using the standardized techniques described by Bindra et al. and²⁷ by Freitas et al.²⁸ for the radius and by Dumont et al.²⁹ and by Aufauvre et al. for the ulna³⁰ (Figure 2). All techniques were used three times to calculate the intra- and interobserver variability (ICCs).

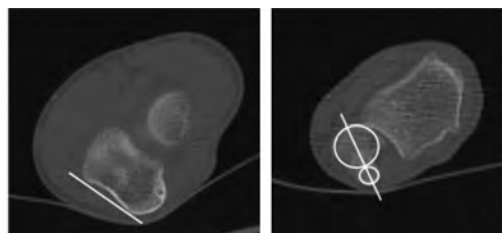


Method of de Freitas et al.



Ulna

Method of Dumont et al.



Method of Aufauvre et al.

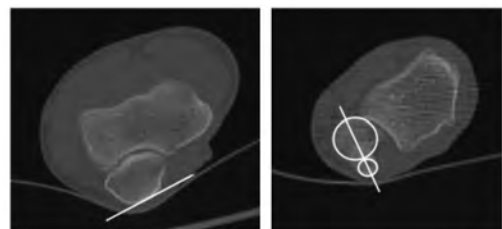


Figure 2. Measurement of torsion angle of radius and ulna by four different techniques.

Magnetic resonance imaging

The fractured forearm was scanned by MRI to visualise contractures of the interosseous membrane, edema, callus formation, periosteal reaction and bony impingement between radius and ulna. The MRI studies were obtained with a 1.0-T magnetic resonance imaging unit (Gyrosan NT, Philips Medical Systems, Best, the Netherlands) using an extremity coil. During MRI the fractured arm was along the body with the forearm placed in full supination. In addition one sequence was obtained while the forearm was placed in full pronation to rule out bony impingement between the radius and ulna as cause of the limitation. We performed coronal T1-weighted turbo spin echo images, coronal and axial fat-suppressed T2-weighted images and axial T1-weighted gradient echo images. The whole forearm was imaged during the coronal, sagittal and axial T1 gradient echo sequences. The axial T2-weighted sequence was obtained from the area around the fracture.

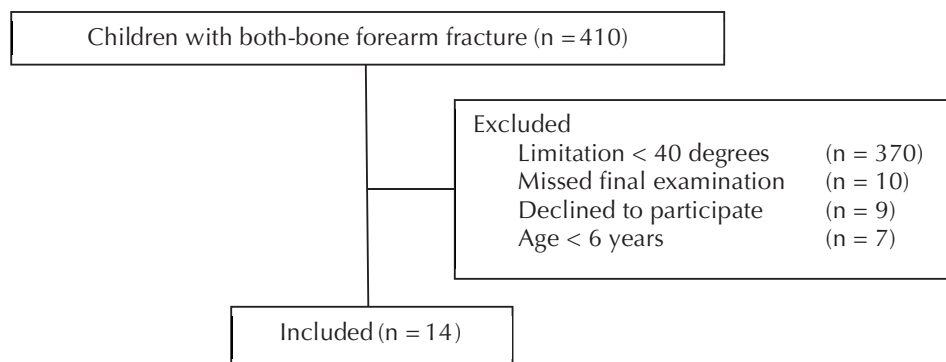
Statistical methods

The results are presented as median (interquartile range (IQR)). When assessing reliability, a distinction between intra-observer and inter-observer reliability was made. Intra-observer reliability investigates the capability of one tester to produce consistent results. Inter-observer reliability examines the extent of concurrence between the results of different observers. The ICCs were calculated using SPSS 17.0 (SPSS Inc., Chicago, USA).

Results

Between January 2006 and August 2010 a total of 410 children with both-bone forearm fractures were followed prospectively. Of these, 30 (7.3%) suffered from a limitation of ≥ 40 degrees of forearm rotation of whom 14 children were included in the present study (Figure 3).

The median age was 12.3 years [interquartile range IQR of 9.5; 14.7] (Table 1). There was an equal distribution of children with a limitation of pronation or supination. At a median of 205 days [IQR 194; 225], the median limitation of pronation and supination was 40 degrees [IQR 40; 55] and the median maximum angular malunion on conventional radiographs was 16 degrees [IQR 13; 19] (Table 3).



n = number of children.

Figure 3. Flowchart of enrolment in the study.

The values of rotational malunion of radius and ulna measured with CT are reported in Table 4. CT analysis showed rotational malunion of both radius (median 19 degrees [IQR 12; 21]) and ulna (median 9 degrees [IQR 4; 12]) with no significant difference ($p=0.07$). Torsion angle measurement of the radius was impossible in 5 children due to imaging problems of the radial tuberosity, i.e. only a part was imaged, the images were oblique and not comparable with the contralateral arm, or the radial tuberosity was not fully developed. In line with this, a not fully developed ulnar styloid precluded measurement of the ulnar torsion angle by the described techniques. For that reason, we used a tangential line that passes the sulcus for the extensor carpi ulnaris as distal reference point for the measurement of torsion (Figure 4). For the different measurement methods, the ICCs for intra-observer reliability were 0.77-0.99 and for interobserver reliability they were 0.69-0.92.

Rotational malunion was defined as the difference in torsion angles of the radius/ulna of the traumatized arm and the non-traumatized arm; Values are

Chapter 11

Table 1. *Outcomes of the study population.*

Child	1	2	3	4	5	6	7
Age in years at time of fracture	8.0	13.9	4.9	14.3	15.7	7.2	10.0
Male gender	-	+	+	+	+	+	-
Dominant arm fractured	+	+	-	-	+	-	+
Number of fracture reductions	1	1	1	1	1	1	1
Stabilization devices	-	-	-	-	TEN	-	-
Days in AEC	26	42	29	41	28	21	21
Days in BEC	15	14	14	0	0	28	21
Complications	-	-	-	-	α β	-	γ
Number of visits physiotherapy	20	12	3	6	10	4	6
Days between fracture and CT/MRI	256	300	218	74	919	265	316

Data in the Total column are presented as median [interquartile range] or percentage; D = diaphysis, M = metaphysis; K = Kirschner wires; AEC = above-elbow cast, BEC = below-elbow cast.

Table 2. *Outcomes of conventional radiography after trauma.*

Child	1	2	3	4	5	6	7
Location of fracture	D	D	M	D	D	D	D
Type fracture radius	g	c	c	c	NR	g	C
Type fracture ulna	g	c	c	c	NR	g	C
Angulation (degrees)							
PA U	30	27	50	2	NR	0	4
PA R	26	34	33	12	NR	4	2
Lat U	56	12	8	6	NR	13	9
Lat R	56	8	3	6	NR	23	21
Translation (% of width)							
PA U	0	0	0	10	NR	0	15
PA R	0	0	95	90	NR	0	0
Lat U	0	60	0	20	NR	0	10
Lat R	0	0	35	0	NR	0	0
Shortening							
Shortening R	-	-	+	-	NR	-	-
Shortening U	-	-	-	-	NR	-	-
Rotation							
Rotation R	-	-	-	-	NR	-	-
Rotation U	-	-	-	-	NR	-	-

D = diaphysis, M = metaphysis; C = complete fracture, G = greenstick fracture; NR = no radiographs available. Lat = lateral; R = radius, U = ulna; Shortening X trauma: + = shortening of radius and/or ulna; radiographs taken at trauma.

3-D imaging of severe limitation of pronation/supination

8	9	10	11	12	13	14	Total
11.1	14.6	15.3	15.2	11.1	13.5	10.2	12.3 [9.5; 14.7]
+	+	+	+	+	+	+	86%
-	-	-	+	-	-	-	36%
2	1	1	1	0	1	1	
-	-	K	-	-	-	-	
47	45	33	27	29	26	18	29 [25; 41]
0	0	0	0	0	0	25	18 [14; 26]
γ δ	α	-	-	α	-	-	
13	24	7	6	0	15	2	7 [4; 14]
776	346	258	217	242	806	274	270 [236; 454]

C = complete fracture, G = greenstick fracture; NR = no radiographs available; TEN = titanium elastic nails.
Complications: α : neurapraxia, β : nonunion ulna, γ : re-fracture, δ : re-reduction

8	9	10	11	12	13	14
D	D	M	M	M	M	D
c	c	c	c	g	c	c
c	c	c	c	g	g	c
2	1	41	40	4	10	ζ
5	1	31	45	6	14	ζ
25	13	55	31	14	32	109
18	11	43	32	7	34	106
20	5	0	100	0	0	0
20	95	40	50	0	45	0
10	0	0	80	0	0	100
0	65	100	90	0	100	0
-	+	+	-	-	+	-
-	-	-	+	-	-	-
-	-	-	+	-	-	-
-	-	-	+	-	-	-

Angulation presented in degrees; Translation presented in percentage of width; PA = posteroanterior, Rotation X trauma: + = rotation of radius and/or ulna; CO = corrective osteotomy done; ζ = no PA

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Table 3. *Outcomes at final follow-up.*

Child	1	2	3	4	5	6	7
Final examination							
Days until final examination	194	197	199	168	274	224	202
Limitation pro	15	35	25	20	30	30	0
Limitation sup	25	5	30	55	15	10	55
Limitation total pro/sup	40	40	55	75	45	40	55
Final radiographs							
Angulation PA U	3	8	0	co	3	1	3
Angulation PA R	1	6	4	Co	1	12	13
Angulation lat U	6	6	0	Co	3	0	13
Angulation lat R	14	12	13	co	1	15	19

Pro/sup = pronation/supination in degrees; PA = posteroanterior, Lat = lateral; U = ulna, R = radius;
Data in the 'Total' column are presented as median and interquartile range.

Table 4. *Outcomes of computed tomography.*

Child	1	2	3	4	5	6	7
Rotational malunion radius							
Bindra et al. observer 1	15	14	*	*	16	35	21
Bindra et al. observer 1	11	19	*	*	8	29	18
Bindra et al. observer 2	24	8	*	*	24	32	22
de Freitas et al. observer 1	31	10	9	*	16	14	2
de Freitas et al. observer 1	25	3	11	*	16	40	1
de Freitas et al. observer 2	19	15	21	*	15	14	2
Total							
Rotational malunion ulna							
Ulnar styloid	-	+	+	-	+	-	+
Dumont et al. observer 1	7	21	2	2	10	25	35
Dumont et al. observer 1	4	16	11	8	6	10	2
Dumont et al. observer 2	5	2	2	8	2	4	19
Aufauvre et al. observer 1	4	4	3	4	7	6	40
Aufauvre et al. observer 1	5	9	1	4	5	2	12
Aufauvre et al. observer 2	44	8	1	5	2	4	38
Total							

3-D imaging of severe limitation of pronation/supination

8	9	10	11	12	13	14	Total
Final examination							
193	305	193	208	209	209	227	205 [194; 225]
70	25	10	35	30	20	20	25 [19; 31]
5	15	30	20	10	20	20	20 [10; 30]
75	40	40	55	40	40	40	40 [40; 55]
Final radiographs							
9	7	8	3	3	5	17	3 {3;8}
7	18	5	18	5	18	5	6 {5;16}
8	7	4	4	8	2	10	6 {3;8}
20	11	5	19	16	10	13	13 {11;18}

8	9	10	11	12	13	14	Total
11	*	11	*	*	35	7	15 [11;28]
9	*	17	*	*	41	1	17 [9;24]
27	*	11	*	*	30	14	24 [13;29]
19	*	7	*	5	6	4	9 [5;16]
29	*	25	*	2	2	22	16 [2;25]
26	*	4	*	12	18	64	15 [12;21]
							19 [12;21]
+	+	+	+	-	+	+	
7	1	1	19	15	7	12	9 [2;20]
15	5	5	17	15	10	13	10 [5;15]
14	1	2	25	8	1	20	5 [2;15]
12	1	6	6	1	0	4	4 [3;6]
16	13	1	23	9	7	3	6 [3;12]
13	2	3	3	3	3	7	4 [3;9]
							9 [4;12]

rotational malunions and presented in degrees; * = measurement not possible; + ulnar styloid used for measurement; - ulnar styloid not used for measurement; Data in the 'Total' column are presented as median [interquartile range] in degrees; No significant difference was found between the total rotational malunion of radius and ulna ($p=0.07$).

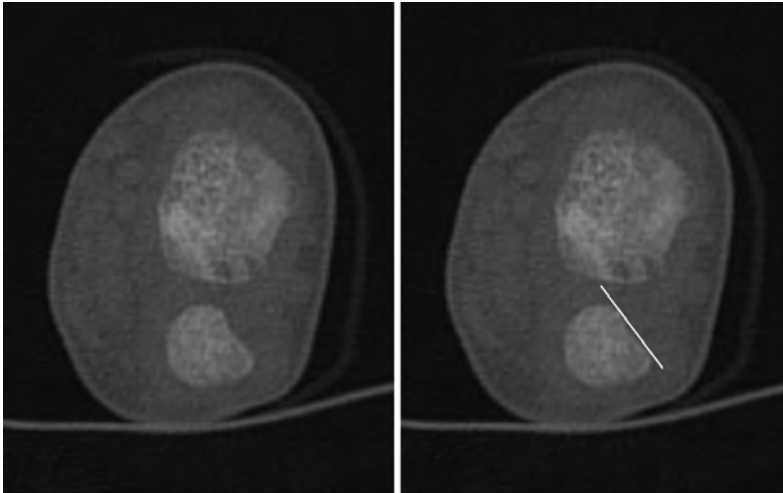


Figure 4. *If ulnar styloid was not full-grown, a tangential line passes the sulcus for the extensor carpi ulnaris was used as a distal reference point for measurements of torsion angle of the ulna.*

Table 5. *Outcomes of magnetic resonance imaging.*

Child	1	2	3	4	5	6
Contracture interosseous membrane	0	0	0	0	0	0
Oedema	0	0	0	2	0	0
Periosteal reaction	0	0	0	2	0	0
Synostosis	0	0	0	0	0	0
Callus	1	1	0	2	0	1
Bony impingement	0	0	0	0	0	0

0 = no pathology, 1 = moderate pathology, 2 = severe pathology.

The outcomes on MRI showed neither contractures of the interosseous membrane nor bony impingement between radius and ulna (Table 5); oedema, periosteal reaction and callus formation around the fractures was found in 29% of children.

DISCUSSION

This prospective study evaluated severe limitation of pronation/supination using 3D imaging in children who sustained a both-bone forearm fracture. CT analysis showed rotational malunions of both radius and ulna, MRI demonstrated neither contractures of the interosseous membrane nor bony impingement.

Although several studies measured the torsion angle of radius and ulna by CT in cadavers or in healthy volunteers²⁷⁻³⁰, we found this technique difficult to apply in our group of children²⁷. Malalignment of the forearm and the severe limitation of pronation/supination made it difficult for children to place the volar aspect of the elbow flat on the table. This resulted in scans with only a part of the radial tuberosity imaged or different angles of images of the radial tuberosity, making comparison difficult between the injured and uninjured site. Furthermore, measurement of torsion angle was impossible in some children with not fully developed radial tuberosity.

Because we encountered the same problem with the measurement of ulnar torsion in case of a not-ossified ulnar styloid, a new technique was applied that showed an inter- and intra-observer reliability that was similar to previously used techniques.

7	8	9	10	11	12	13	14
0	0	0	0	0	0	0	0
2	0	0	1	2	0	0	0
1	0	0	1	1	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Torsion angle of the radius

Bindra et al. measured the torsion angle of the radius with CT and Dumont et al. repeated this measurement using MRI. The ICCs for intra-observer reliability (0.88 and 0.95) and inter-observer reliability (0.94 and 0.82) of both studies were similar to ours (0.98 and 0.85). Freitas et al. also measured the torsion angle of the radius and found ICCs for intra-observer reliability of 0.28-0.91 and for inter-observer reliability of 0.75-0.90. The ICCs in the present study were relatively high with 0.92-0.99 for intra-observer reliability and 0.69-0.78 for inter-observer reliability.

Torsion angle of the ulna

Dumont et al. measured the torsion angle of the ulna using MRI and found an ICC for intra-observer reliability of 0.95 and an ICC for inter-observer reliability of 0.91. The ICCs in the present study were 0.80-0.88 for intra-observer reliability and 0.85-0.87 for inter-observer reliability. In their study, Aufauvre and colleagues did not measure ICCs.

Magnetic Resonance Imaging

Our MRI findings showed only a few alterations, which were in line with an earlier study (20). In our study group, oedema, callus and periosteal reaction detected on MRI may be normal in the healing process of severe both-bone forearm fractures. While impingement is mentioned as a potential cause of limitation of pronation/supination after forearm fractures, we found no impingement between the radius and ulna in maximum pronation/supination^{9,11,19}. Although studies have described the important role of contractures of the interosseous membrane in limitation of pronation/supination after forearm fractures, in our study group these were not detected on MRI^{9,11,22-24}. However, the question remains whether the contractures did not in fact exist, or whether they were not detectable on MRI.

Study limitations

Our CT protocol did not succeed in visualizing all radial tuberosity's, which precluded determination of the torsion of the radius in some children. This could have been avoided by using a CT of both whole forearms with a bone and a soft tissue setting. Different angles of anatomical landmarks between the two forearms

could have been corrected using an isotropic dataset. In this way, the soft tissue window could have visualized the insertion of the biceps tendon that might serve as a reference for the radial tuberosity. Nevertheless, this technique would also not visualize the tuberosity's that were not fully developed. Furthermore, this method of scanning employs a higher dose of radiation which is potentially hazardous for children.

MRI of both arms with a higher resolution might have detected more soft tissue pathology. However, the sparse availability of the MRI unit made scanning of both arms impossible and the use of an extremity coil compensated for the relatively low resolution.

Ideally our follow-up period should have been longer in this young population to see if correction of malunion by growth would have influenced the limitation of forearm rotation.

CONCLUSION

This prospective study evaluated severe limitation of pronation/supination using 3D imaging in children who sustained a both-bone forearm fracture. The MRI demonstrated neither contractures of the interosseous membrane nor bony impingement. CT analysis showed rotational malunions of both radius and ulna. Because malunion, impaired forearm rotation and a not fully developed radial tuberosity hindered measurement of rotational malunion in several children, further research should be done with a CT of both whole forearms with a bone and a soft tissue setting.

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PART VI

GENERAL DISCUSSION AND SUMMARY

CHAPTER 12

General discussion

PART 1 METAPHYSEAL BOTH-BONE FRACTURES OF THE DISTAL FOREARM

Metaphyseal both-bone fractures of the distal forearm are among the most frequent fractures in childhood. This thesis reveals that minimally displaced fractures can be safely treated in a below-elbow cast, which is supported by previous studies¹⁻³. In case of a displaced fracture the clinician is often confronted with a treatment dilemma, i.e. whether to accept some degree of displacement, or to perform a reduction of the fracture. A perfect anatomical fracture alignment is not always necessary in children because natural growth remodels malalignment. The highest remodelling by growth takes place in fractures that are close to the most active distal growth plate. Therefore, previous studies stated that metaphyseal fractures of the distal forearm with an angulation ≤ 15 degrees can be treated without reduction in children of all ages⁴. In accordance with these findings, we found that children with an angular malalignment of ≤ 15 degrees had a less than 13% chance to develop a clinically relevant limitation (i.e. < 50 degrees of pronation and/or supination), while children with an angular malalignment of ≥ 16 degrees had a 60% chance.

Therefore, fractures in which the angulation exceeds 15 degrees need to be reduced in the operating room under general anaesthesia with fluoroscopic guidance. Because this thesis shows that secondary displacement of these reduced fractures occurred in 45% of children treated with only an above-elbow cast, we advise to perform stabilisation of the radius fracture by means of two crossed percutaneous Kirschner wires (K-wires). In this case, the surgeon should also consider stabilisation of an unstable ulnar fracture, because secondary fracture displacement of the ulna was seen in 5% of children in which only the radius was stabilised with K-wires. Whereas some groups buried the K-wires subcutaneously, requiring an additional operation for removal⁵, in our study the K-wires were placed transcutaneously to facilitate removal in the outpatient clinic. Nevertheless, in our study, 11% of the K-wires became subcutaneous thereby making an additional operation necessary. This complication might have been avoided by not cutting the K-wires too short. Although the K-wires were placed transcutaneously, only 3% of the children in our study developed a superficial infection; this rate is similar to that reported by others⁶. In our study, no child had symptoms of neuromas of either the radial sensory nerve, lateral cutaneous nerve of the forearm, or posterior cutaneous

nerve of the forearm. This may be explained in two ways: by using a proper surgical technique with a small skin incision and blunt dissection of soft tissue and, secondly, due to the less vulnerable nerves in children; this is confirmed by the absence of literature reporting on iatrogenic neuromas in childhood.

PART 2 DIAPHYSEAL BOTH-BONE FOREARM FRACTURES

Because of the relatively long distance between a diaphyseal fracture and the distal and proximal growth plates, only minimal correction of malalignment by growth can be expected. A previous study stated that diaphyseal fractures in children need to be reduced in accordance with their age, i.e. in children up to 9 years of age an angulation up to 15 degrees can be expected, while in children 9 years of age or older, 10 degrees of angulation is acceptable⁴. Nevertheless, in our opinion also fractures with less angulation might benefit by reduction because our results indicate that children with ≤ 5 degrees of angular malalignment already have a 13% chance to develop a clinically relevant limitation (i.e. < 50 degrees of pronation and/or supination).

Based on the results of our randomised controlled study, diaphyseal both-bone forearm fractures without need for reduction could be safely be treated with an above-elbow cast for 3 weeks, followed by a below-elbow cast. In general, among our group of children, 6 weeks of cast was long enough. Nevertheless, painful fractures without formation of callus on radiographs should be treated in cast for a longer period. Because even minimally displaced fractures showed a tendency for secondary displacement in cast, radiographs at weekly intervals until removal of the cast should be made to avoid malalignment.

Displaced diaphyseal both-bone forearm fractures should be reduced in the operation room under general anaesthesia with fluoroscopic guidance. If the reduction is easy and the fracture seems to be stable, an above-elbow cast has to be applied to stabilise the fracture. Similar to the treatment of the non-reduced fractures, following the results of our randomised controlled study, the above-elbow cast can be safely replaced by a below-elbow cast after 3 weeks.

Compared with previous studies, limitation of pronation/supination was relatively high in our group of diaphyseal both-bone fractures⁷⁻¹³. Using the grading

system (9) we found 21-33% excellent results, whereas others found excellent results in 44-100%. Previous studies reported a re-displacement rate of 7-27% in conservatively treated forearm fractures^{7,10,11,14-17} whereas our rate was 23-34%.

Fractures that seem to be unstable during reduction should be stabilised with intramedullary nails. Several non-randomised and mostly retrospective studies advocated stabilisation of both-bone forearm fractures with only one intramedullary nail in either the radius or ulna, in combination with a supplementary cast¹⁸⁻²⁸. In those studies, the surgeon could choose per-operatively for single-bone or both-bone fixation depending on the stability of the fracture, whereas we performed a study with randomisation between one or two intramedullary nails irrespective of the fracture stability. The group of children treated with one intramedullary nail showed inferior results because of displacement of the non-fixated bone. Such re-displacement in single-bone intramedullary fixation of both-bone forearm fractures is not uncommon^{19,20,24,27}. We suggest that these unstable diaphyseal fractures should be stabilised with an intramedullary nail in both the radius and ulna to prevent re-displacement and to enable unloaded exercises of the arm without cast to improve final function.

PART 3 FRACTURE DISPLACEMENT

A both-bone forearm fracture destabilises the structural columns of the forearm. Although the clinician tries to re-stabilise the fractured forearm by cast, K-wires, intramedullary nails or plates, fracture displacement occurs frequently. Previous studies described fracture displacement of 7-91% in the distal metaphysis^{17,29-36} compared to 33% in our study, and fracture displacement in the diaphysis^{7,10,11,14-17,37} was found in 7-52% compared to 27% in our study. There are several explanations for our relatively high percentage of displacement. First, we included only both-bone forearm fractures that are notorious for instability^{1,38}. Second, we had a detailed prospective follow-up with scheduled radiographs. Third, our malalignment criteria were relatively strict, especially for young children with a high potential for remodelling by growth. Fourth, a non-circumferential cast was applied directly after reduction. Finally, the test used to distinguish between stable and unstable fractures might have been influenced by the opinion of the surgeon.

As expected, fractures stabilised by K-wires or intramedullary nails showed less displacement than fractures treated with cast only. However, also in this group, displacement was seen by improper surgical technique or displacement of the non-fixated bone.

Our prospective multivariate regression analysis revealed fractures of the non-dominant arm to be a risk factor for fracture displacement in cast, which was not found by others^{34,39}. Less stability of the fracture by less developed muscles in the non-dominant forearm might be an explanation for this increased risk of fracture displacement in the non-dominant forearm. Furthermore, our analysis showed that the severity of fracture displacement directly after the trauma is highly predictive for secondary displacement in cast. In more detail: complete fractures were at higher risk for displacement than greenstick fractures, a finding supported by some clinicians^{15,34,36,40,41} but not by others^{17,42}. Fractures with translation of the ulna on lateral radiographs were at risk for displacement, as reported once before¹⁵. Shortening of fractures has not previously been reported as a risk factor. Thus, in our study, fracture angulation did not appear to be a risk factor for displacement, as also found in previous studies^{34,42}. In summary, complete fractures with translation and shortening seem to be more unstable than angulated greenstick fractures with an intact periosteal sleeve on one side.

Several studies reported that the quality of the cast (cast index) is a risk factor for fracture displacement^{2,17,40,42}; however, this was not supported by our studies and by others^{15,41}. Although an above-elbow cast was generally considered more likely to prevent fracture displacement than a below-elbow cast, we found a tendency towards less fracture displacement in children treated with a below-elbow cast. This finding has been reported before and might be explained by several theories¹⁻³. First, the application of an above-elbow cast might be more difficult, resulting in an inferior cast with less three-point fixation. Second, an above-elbow cast restricts wrist and elbow motion and, therefore, induces forced movements of the fractured arm in daily use. Third, elbow motion in a below-elbow cast results in micro-movements in the fracture, which facilitates secondary fracture healing. Finally, it is possible that an above-elbow cast results in more atrophy with less stabilising soft tissue around the fracture.

Our results suggest that a diaphyseal or metaphyseal location of the fracture

has no significant influence on displacement, a finding supported by one group^{15,39} but not by another^{15,39}. Furthermore, we found no significant effect of reduction with or without general anaesthesia^{36,39}. Although fracture displacement occurred more frequently in the group of reduced fractures than in non-reduced fractures, clinicians should also be aware of secondary displacement of minimally displaced fractures.

Similar to other studies^{1,5,34} only half of our re-displaced fractures were reduced a second time, although this was suggested in our study protocol. Although not planned, this illustrates the restraint of treating clinicians to decide on a second reduction. On the one hand, the surgeon may hope or expect correction of the malalignment by growth whereas, on the other hand, the surgeon may be reluctant to burden the child again or may find it difficult to accept failure of the initial treatment. Nevertheless, the results of our study revealing the relation between malunion and limitation of pronation/supination, suggest that better functional results are achieved if clinicians follow the study protocol.

In conclusion, all both-bone forearm fractures in children need to be monitored carefully using weekly radiographs to enable early detection of fracture displacement. In case of displacement, the clinician should bear several factors in mind when considering treatment, i.e. the severity of displacement, fracture in the dominant arm, age of the child, and the distance between the fracture and the most active distal growth plate.

PART 4 LIMITATION OF FOREARM ROTATION

Although most of the both-bone forearm fractures heal uneventfully, limitation of pronation and supination can give disappointing results^{11,43-45}. While movement of the ipsilateral shoulder can compensate mild limitation of pronation/supination, more severe limitation hinders daily activities. To function properly both pronation and supination need to be at least 50 degrees⁴⁶; in our study this was not obtained by 20% of the children after a mean period of 218 (\pm 49) days. In our study the mean limitation of forearm rotation was 12 (\pm 14) degrees. Despite the absence of other prospective studies, our results seem to be slightly less successful than other series. This might be explained in several ways. First, we only included children with

relatively severe injuries that resulted in fractures of both the radius and the ulna. Second, ours was a prospective study with a precise registration of arm function. Third, we included many diaphyseal fractures, which are prone to impaired forearm rotation. Fourth, a relatively large number of fractures healed in malalignment, which increases the chance of limitation of forearm rotation. Finally, the relatively short follow-up period, with less correction of malalignment by growth, had a negative impact on our results.

Although not fully elucidated in literature, malunion and soft tissue contractures are generally thought to cause impaired forearm rotation after a forearm fracture. An interaction between these two causes may occur when a malunion changes the tension of the interosseous membrane⁴⁷⁻⁵⁰.

Limitation of pronation/supination attributed to malunion consists of malalignment in angulation, translation or rotation^{12,47,49,51-56}. Whereas some reported that angular malalignment may result in significant limitation^{47,48,51,57}, others found a poor correlation between residual angular malunion and the final range of pronation/supination^{12,43,45,48,58-60}. In our multivariate logistic regression analysis, angular malalignment was not independently associated with a limitation of pronation/supination. However, our clinical study relating impaired forearm rotation with angular malalignment showed that angular malalignment in fractures resulted in a clinically relevant limitation of pronation/supination.

Malalignment in translation is considered to cause impingement between the forearm bones, resulting in limitation of pronation and supination^{49,54-56}. However, in our study, the primary translational displacement of the fracture was changed by appositional periosteal bone formation and at final follow-up only minimal callus without notable translational malalignment was seen on the radiographs. Furthermore, magnetic resonance imaging of children in our study population who suffered from a severe limitation revealed no bony impingement between the radius and ulna.

In cadaver studies rotational malalignment of the ulna and radius caused limitation of forearm rotation^{52,53,55}. Our clinical study with computer tomography confirmed a rotational malalignment of both the radius and ulna in children suffering from severe limitation of pronation/supination.

Several studies suggested that soft tissue contractures following forearm fractures lead to limitation of pronation/supination^{50,54,61-63}. These contractures may

originate from muscles, capsules and the interosseous membrane. It is reported that a volar fracture haematoma following a distal radius fracture caused a contracture of the pronator quadratus muscle, with subsequent a limitation of supination⁶⁴. In line with this, a fracture haematoma of the pronator quadratus muscle and the pronator teres muscle can result in contractures with limitation of supination, while contractures of the supinator muscle and the biceps muscle can result in limitation of pronation. Because we found more limitation of pronation than supination (29% vs. 23%) in distal metaphyseal both-bone forearm fractures, we assume that contractures of the pronator quadratus muscle are probably not the main cause of limitation. Furthermore, if contracture of the biceps muscle plays a role in the limitation of pronation, then we would also expect a limitation of elbow extension because the biceps muscle acts as both a supinator and an elbow flexor.

Contractures of the capsule of wrist and elbow have been reported as a cause of impaired forearm rotation^{50,63}. However, this argument is not applicable in our study population, because capsule contractures should have also led to impaired flexion and extension of wrist and elbow, which was not the case in our children.

Our multivariate analysis revealed a diaphyseal fracture to be an independent risk factor for limitation of forearm rotation. Thereby, diaphyseal fractures with minimal angular malalignment (≤ 5 degrees) already had a 13% chance of severe limitation of forearm rotation and this chance showed no significant increase with more severe malalignment. Therefore, we assume that contractures of the interosseous membrane play an important role in the limitation of pronation/supination in diaphyseal fractures. This can be explained in several ways. First, in our study, because about 75% of diaphyseal fractures were severe displaced, we assume that the high force of injury that fractures the thick cortices of both the radius and ulna is associated with significant injury to the interosseous membrane. Second, previous studies described five ligamentous components of the interosseous membrane, of which only the two most proximal cords showed a substantial change in length during forearm rotation⁶⁵. Immobilisation of a diaphyseal fracture in an above-elbow cast might result in a reduced amount of lengthening of these injured proximal cords and, consequently, impairment of forearm rotation. Other independent risk factors revealed in our multivariate analysis were less physiotherapy and re-fractures. Both of these suggest a substantial role of soft tissue contractures

in limitation of forearm rotation: while physiotherapy decreases contractures by stretching, a re-fracture gives rise to more contractures by an extra injury in regenerating soft tissue. Finally, contractures of the interosseous membrane as a cause of limitation of forearm rotation was confirmed in a study that found a correlation between initial fracture displacement, MRI-detected interosseous membrane alternations, and limitation of pronation/supination⁶⁶.

Furthermore, pathology of the distal or proximal radio-ulnar joint may impair forearm rotation. Although pathology in these joints seems obvious in Galeazzi or Monteggia fracture dislocations, tightening of the triangular fibrocartilage complex has also been described as a cause of impaired forearm rotation following radius fractures⁶⁷⁻⁶⁹. Nevertheless, we assume that pathology of the distal or proximal radio-ulnar joint mainly occurs if the energy of impact causes a single-bone fracture and soft tissue injury along the other bone.

Taking all these findings into consideration, we conclude that only children with a severe angular malalignment of a metaphyseal fracture have a high risk of impaired forearm rotation, while children with diaphyseal fractures have a moderate chance to develop a limitation irrespective of the severity of the angular malalignment. In this latter group we expect a contracture of the interosseous membrane to play a substantial role, even though we were unable to detect it on (low resolution) MRI. Impingement between malunions of the radius and ulna did not affect limitation, and rotational malunion seems to have some influence but is, however, difficult to detect.

Overall, the work in this thesis has revealed more insight in the treatment and complications of both-bone forearm fractures in children.

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CHAPTER 13

Recommendations for future research

Although this thesis aimed to further enhance the knowledge on both-bone forearm fractures in children, several questions remain to be answered. The results of this thesis were based on a follow-up period of approximately 7 months. Therefore, a longer period of follow-up may provide new insights into the role of (corrected) malunions on impaired forearm rotation.

Thereby, conservatively treated fractures might benefit from improved treatment with cast, i.e. direct application of circumferential cast by a cast technician.

Because we allocated reduced metaphyseal both-bone fractures of the distal forearm to treatment with an above-elbow cast with or without additional Kirschner wires, we still do not know whether such fractures can be treated by Kirschner wires and a below-elbow cast.

Although we considered soft tissue contractures to be an important contributor of impaired forearm rotation, our magnetic resonance imaging (MRI) study could not confirm this. Therefore, a MRI with a higher resolution may expose soft tissue contractures.

Furthermore, computed tomography (CT) of both whole forearms with a bone and a soft tissue setting may reveal the complex configuration of a malunion and may make three-dimensional corrective osteotomy using a computer simulation system possible.

Finally, the development of a treatment algorithm for children with impaired forearm rotation after a both-bone forearm fracture will probably be very helpful.



CHAPTER 14

General summary

This thesis aimed to unravel several aspects of both-bone forearm fractures in children by conducting a prospective randomised controlled study which included 410 children in four Dutch hospitals. Finally, a total of 400 children were assessed both clinically and radiologically at a mean of 218 (\pm 49) days.

PART 1 METAPHYSEAL BOTH-BONE FRACTURES OF THE DISTAL FOREARM

In **Chapter 2** children with minimally-displaced metaphyseal both-bone fractures of the distal forearm were randomised to 4 weeks below-elbow cast (**BEC**) or 4 weeks above-elbow cast (**AEC**). Children treated with BEC encountered higher cast comfort and needed less help with dressing; furthermore, the BEC group showed fewer complications. In conclusion, children with a minimally-displaced metaphyseal both-bone fracture of the distal forearm should be treated with a BEC.

The children investigated in **Chapter 3**, who sustained a displaced metaphyseal both-bone fracture of the distal forearm that was stable after reduction, were randomised to AEC with or without percutaneous fixation with Kirschner wires. The group of children treated with additional pinning showed less re-displacement, less limitation of pronation and supination, but more complications. This study demonstrated that pinning of apparently stable both-bone fractures of the distal forearm in children reduces fracture re-displacement. Furthermore, the frequently seen complications of pinning might be reduced by a proper surgical technique.

PART 2 DIAPHYSEAL BOTH-BONE FOREARM FRACTURES

In **Chapters 4** and **5** we studied children with diaphyseal both-bone forearm fractures which were either non-reduced or stable after reduction. These children were randomly allocated to 6 weeks AEC, or to 3 weeks AEC followed by 3 weeks BEC. The results showed that the limitation of pronation/supination was similar in both groups. Thereby, all secondary outcomes (re-displacement of the fracture, limitation of flexion/extension of wrist and elbow, complication rate, assessments of radiographs, complaints in daily life and cosmetics of the fractured arm) were similar in both groups, with the exception of cast comfort - which was in favour of the BEC group only in the reduced fracture group. Therefore, we conclude that early

conversion to BEC cast in these children is safe and results in greater cast comfort.

Chapter 6 cautions against the use of single-bone fixation in all diaphyseal both-bone forearm fractures that are unstable after reduction. Single-bone fixation leads to increased re-displacement, (longer) cast immobilisation, and inferior clinical results.

PART 3 FRACTURE DISPLACEMENT

The aim of the study presented in **Chapter 7** was to identify risk factors for fracture displacement of both-bone forearm fractures treated with cast, by means of multivariate logistic regression analyses. Both-bone forearm fractures in children have a strong tendency to displace, even in an above-elbow cast. The risk factors that, independently of each other, significantly increased the risk of fracture displacement were severe fractures (a complete fracture, a fracture with translation of the ulna on the lateral radiograph, and shortening of the fracture) of the non-dominant arm.

PART 4 LIMITATION OF FOREARM ROTATION

The study presented in **Chapter 8** compared the intra- and interrater reliability of visual estimation and conventional goniometry in the determination of forearm rotation in paediatric patients that had previously sustained a both-bone forearm fracture. The results showed that the intra- and interrater reliability of visual estimation and conventional goniometry was fair to excellent, with lower smallest detectable differences in the conventional goniometry group. Thus, a conventional goniometer is an easy, fast and reliable method to determine the pronation and supination in a child who has sustained a forearm fracture. If an uncooperative child hinders the measurement, visual estimation is a good second choice. Finally, measurements proved to be more reliable when repeated by the same professional.

Chapter 9 describes which clinical factors are related to the limitation of pronation/supination in children with a both-bone forearm fracture, based on multivariate logistic regression analyses. The results imply that a re-fracture, a fracture in the diaphysis, and less physiotherapy during follow-up, were independently associated with a limitation of pronation/supination of 20 degrees or more.

In **Chapter 10** we aimed to predict the limitation of pronation/supination by the degree of angular malalignment. The results show that fractures localised in the distal metaphysis had a greater chance to develop a clinically relevant limitation of forearm rotation in case of a more severe angular malalignment, while diaphyseal fractures had a moderate chance of limitation independent of the severity of the angular malalignment.

In **Chapter 11** we used three-dimensional imaging to evaluate malalignment, bony impingement and contractures of the interosseous membrane as a cause of severe limitation of forearm rotation following a both-bone forearm fracture in children. Conventional radiography, computed tomography (CT) and magnetic resonance imaging (MRI) revealed angular and rotational malunions of both radius and ulna without bony impingement or soft tissue contractures.





HOOFDSTUK 15

**General summary in Dutch /
Samenvatting in het Nederlands**

BREUKEN VAN ZOWEL HET SPAAKBEEN ALS DE ELLEPIJP

Dit proefschrift gaat over kinderen die een breuk hebben opgelopen van zowel het spaakbeen als de ellepijp. In het Latijn wordt deze breuk de *fractura antebrachii* genoemd. De basis van dit proefschrift betreft een onderzoek met deelname van 410 kinderen in 4 verschillende ziekenhuizen. De behandeling van deze kinderen werd bepaald door loting tussen twee behandelingsvormen. Na gemiddeld 218 dagen werden 400 kinderen op de polikliniek teruggezien en werden röntgenfoto's gemaakt. Met deze gegevens werd geanalyseerd welke behandeling het beste is voor welk type breuk. De breuken zijn in te delen naar locatie (dichtbij de pols of in het midden van de onderarm), naar de mate van verplaatsing (weinig of fors verplaatst) en naar de mate van stabiliteit (stabiel of instabiel). De resultaten van de verschillende behandelingen zijn gerapporteerd in deel 1 en 2, terwijl de verplaatsing van de breuk in gips en verminderde functie van de onderarm aan bod komen in deel 3 en 4.

DEEL 1 BREUKEN DICHTBIJ DE POLS

In **hoofdstuk 2** wordt een studie beschreven over de behandeling van breuken van zowel het spaakbeen als de ellepijp dichtbij de pols. Deze breuken waren weinig verplaatst en hoefden daarom niet in goede positie gezet te worden. Bij deze kinderen werd er geloot tussen een behandeling met gips tot aan de elleboog (onderarmgips) en gips voorbij de elleboog (bovenarmgips). De resultaten toonden dat de groep kinderen met onderarmgips het gips comfortabeler vonden en minder hulp nodig hadden met aankleden. Ook werden er minder complicaties gezien in deze groep. Concluderend kunnen kinderen met een weinig verplaatste breuk dichtbij de pols beter behandeld worden met een onderarmgips.

Hoofdstuk 3 gaat over kinderen met een fors verplaatste breuk dichtbij de pols waarbij het nodig was de breuk in goede positie te zetten in de operatiekamer. Nadat de breuk in goede positie was gezet, werd de stabiliteit van de breuk getest. Bij stabiele breuken werd er geloot tussen de behandeling met alleen bovenarmgips en een combinatie van 2 ijzeren pennetjes ter stabilisatie van de breuk en bovenarmgips. In de groep kinderen behandeld met een combinatie van 2 ijzeren

pennetjes en bovenarmgips werden minder verplaatsing van de breuk, een betere functie maar meer complicaties gezien ten opzichte van de groep behandeld met alleen bovenarmgips. Derhalve kunnen deze breuken beter gestabiliseerd worden met 2 ijzeren pennetjes om verplaatsing van de breuk tegen te gaan. Wel is een nauwkeurige chirurgische techniek noodzakelijk om complicaties te vermijden.

DEEL 2 BREUKEN IN HET MIDDEN VAN DE ONDERARM

Bij breuken van zowel het spaakbeen als de ellepijp in het midden van de onderarm werd een onderscheid gemaakt tussen weinig en fors verplaatste breuken, waarbij alleen de fors verplaatste breuken in goede positie werden gezet. Na het in goede positie zetten van de fors verplaatste breuken werd een onderscheid gemaakt tussen stabiele en instabiele breuken. Bij de weinig verplaatste breuken (studie beschreven in **hoofdstuk 4**) en de breuken die na het in goede positie zetten stabiel waren (studie beschreven in **hoofdstuk 5**), werd er geloot tussen de behandeling met respectievelijk 6 weken bovenarmgips en een combinatie van 3 weken bovenarmgips en 3 weken onderarmgips. In beide studies waren de resultaten tussen de twee groepen vergelijkbaar met uitzondering van een hoger comfort in gips in de groep behandeld met boven- en onderarmgips. Concluderend kunnen zowel weinig verplaatste breuken als fors verplaatste breuken die na het in goede positie zetten stabiel waren, het beste behandeld worden met een combinatie van boven- en onderarmgips.

Hoofdstuk 6 beschrijft de fors verplaatste breuken in het midden van de onderarm die na het in goede positie zetten instabiel waren. Deze breuken werden volgens loting gestabiliseerd met 1 of 2 pennen in het spaakbeen en/of de ellepijp. Breuken die werden gestabiliseerd met 1 pen vertoonden meer verplaatsing, werden langer behandeld met gips en hadden minder goede klinische resultaten. Derhalve kunnen deze breuken het beste worden gestabiliseerd met zowel een pen in het spaakbeen als in de ellepijp.

DEEL 3 VERPLAATSING VAN DE BREUK IN GIPS

Breuken van zowel het spaakbeen als de ellepijp hebben de neiging om te verplaatsen in gips. Om te onderzoeken welke factoren van invloed zijn op het verplaatsen van deze breuken in gips werden in **hoofdstuk 7** de risicofactoren in kaart gebracht. Hieruit bleek dat met name zeer ernstige breuken van de niet dominante arm vaker verplaatsten in gips.

DEEL 4 VERMINDERDE ROTATIE VAN DE ONDERARM NA DE BREUK

Bij rotatie van de onderarm draait het spaakbeen om de ellepijp heen. Door een breuk van beide botten kan een verminderde rotatie in de onderarm ontstaan. Om de rotatie van de onderarm te meten gebruikt men vaak een gradenboog, de goniometer. In **hoofdstuk 8** wordt de rotatie van de onderarm respectievelijk geschat en gemeten met een goniometer. Uit de resultaten blijkt dat het meten met een goniometer nauwkeuriger is dan het schatten van de rotatie. Ook is een vervolgmeting nauwkeuriger als dezelfde onderzoeker de meting herhaalt. In **hoofdstuk 9** blijkt dat er drie onafhankelijke risicofactoren van invloed zijn op verminderde rotatie van de onderarm na een breuk van zowel het spaakbeen als de ellepijp; een recidief breuk, een breuk in het midden van de onderarm en weinig fysiotherapie. In **hoofdstuk 10** werd onderzocht of het in een verkeerde positie vastgroeien van een onderarmbreuk van invloed is op een verminderde rotatie van de onderarm. Hieruit bleek dat er hoog risico was op het ontwikkelen van verminderde rotatie in geval van forse scheefstand bij breuken dichtbij de pols enerzijds, en in geval van milde scheefstand bij breuken in het midden van de onderarm anderzijds. In **hoofdstuk 11** wordt 3-dimensionaal radiologisch onderzoek (MRI en CT) gebruikt om meer inzicht te krijgen in de oorzaak van de verminderde rotatie na een onderarmbreuk. Hieruit kwam naar voren dat, (1) deze breuken in een verkeerde rotatiestand kunnen vastgroeien, (2) dat er geen sprake was van botsen tussen het spaakbeen en de ellepijp tijdens rotatie en (3) dat er geen verlittekening was van de weke delen tussen het spaakbeen en de ellepijp.

PART VII

APPENDICES



PhD Portfolio



PHD PORTFOLIO

COURSES

Scientific writing in English for publication, Rotterdam	2011
Developing a Cochrane systematic review, Amsterdam	2007
Evidence based surgery in clinical practice, Zwolle	2005

ORAL PRESENTATIONS

Which factors affect limitation of pronation/supination after forearm fractures in children? A prospective multicentre study. Dutch Orthopaedic Association. Rotterdam	2014
Risk factors for the displacement of fractures of both-bones of the forearm in children. Dutch Orthopaedic Association. Rotterdam	2014
Risk factors for the displacement of fractures of both bones of the forearm in children. Dutch trauma meeting, Amsterdam	2013
Re-displacement of stable distal both-bone forearm fractures in children: A randomised controlled multicentre study. Netherlands Society for Hand Surgery, Amsterdam	2012
Below-elbow cast for metaphyseal both-bone fractures of the distal forearm in children: A randomized multicentre study. Dutch Orthopaedic Association. Veldhoven	2012
Re-displacement of stable distal both-bone forearm fractures in children: A randomised controlled multicentre study. Federation of European Societies for Surgery of the Hand, Antwerp	2012
Re-displacement of stable distal both-bone forearm fractures in children: A randomised controlled multicentre study. Congress of the European Paediatric Surgeons Association, Rome	2012

PhD Portfolio

Both-bone forearm fractures in children. The first results. Trauma meeting ZWOT, Rotterdam	2012
Conversion to below-elbow cast after 3 weeks is safe for diaphyseal both-bone forearm fractures in children. Dutch Surgery Society, Ede	2011
Re-displacement of stable distal both-bone forearm fractures in children: A randomised controlled multicentre study. Dutch Surgery Society, Ede	2011
Re-displacement of stable distal both-bone forearm fractures in children: A randomised controlled multicentre study. Dutch trauma meeting, Amsterdam	2011
Both-bone forearm fractures in children. The results of a multicentre study with inclusion of 410 children. Dutch Society for Paediatric Orthopaedics, Utrecht	2011
INVITED LECTURES	
Below-elbow cast for metaphyseal both-bone fractures of the distal forearm in children: A randomized multicentre study. Dutch Orthopaedic Trauma Society, Amsterdam	2013
Both-bone forearm fractures in children. The results of a multicentre study with inclusion of 410 children. Dutch Society for Paediatric Surgery, Utrecht	2013
Both-bone forearm fractures in children. The results of a multicentre study with inclusion of 410 children. Trauma meeting, Euregio, Hengelo	2013
Both-bone forearm fractures in children. The results of a multicentre study with inclusion of 410 children. Trauma meeting, TOWN, the Hague	2013

Different kind of cast for the treatment of both-bone forearm fractures in children. Dutch trauma meeting, Amsterdam 2011

POSTER PRESENTATIONS

Early conversion to below-elbow cast for displaced diaphyseal both-bone forearm fractures in children: a multicenter randomized controlled trial. Congress of the European Paediatric Surgeons Association. Rome 2012

Pronation and supination after forearm fractures in children: Reliability of visual estimation and conventional goniometry measurement. Dutch trauma meeting. Amsterdam 2010

HONORS AND AWARDS

Biomet price Best scientific research, Dutch Orthopaedic Association 2014

NVOT Award Best scientific article in Orthopaedic Trauma 2012

Best oral presentation of Dutch trauma meeting 2011

SUPERVISING MASTER'S THESIS

Leon Diederix, Resident Orthopaedic Surgery Thesis: 5 years follow-up of both-bone forearm fractures in children 2012-present



List of Publications



List of publications

LIST OF PUBLICATIONS

Colaris JW, Oei S, Reijman M, Holscher H, Allema JH, Verhaar JA. Three-dimensional imaging of children with severe limitation of pronation/supination after a both-bone forearm fracture. *Arch Orthop Trauma Surg.* 2014 Mar;134(3):333-41.

Colaris JW, Allema JH, Reijman M, de Vries MR, Ulas Biter L, Bloem RM, van de Ven CP, Verhaar JA. Which factors affect limitation of pronation/supination after forearm fractures in children? A prospective multicentre study. *Injury.* 2014 Apr;45(4):696-700.

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Curriculum Vitae

A young child with curly hair, wearing a dark Superman t-shirt, is shown from the chest up. The child is looking down and to the right. The right arm is extended downwards, and a glowing white skeletal overlay is visible on the forearm and hand. The background is split into a dark upper half and a light lower half.

CURRICULUM VITAE



Joost Willem Colaris was born on the 29th of February 1976 in Heerde, the Netherlands. He finished secondary school in 1995 at the Stedelijk Gymnasium in Apeldoorn. In the same year he moved to Belgium to study Medicine at the Catholic University of Leuven, where he completed his doctoral degree studies. Before starting his internships at the University of Leiden, he travelled through South-East Asia for 7 months. In 2003 he graduated cum laude.

His career in orthopaedic surgery began as a resident in the Rijnland Hospital in Leiderdorp (Dr. E.J. van Langelaan). In 2004 the residency of general surgery was started at the Rode Kruis Hospital in The Hague (Dr. H. Boutkan). During this period he initiated research that laid the foundation for this thesis. Training in orthopaedic surgery continued in the Leyenburg Hospital in The Hague (Dr. L.N.J.E.M. Coene), Erasmus Medical Center in Rotterdam (Prof. Dr. J.A.N. Verhaar) and the HAGA Hospital in The Hague (Dr. F.W.M. Faber).

In 2010 he became an orthopaedic surgeon at the Erasmus Medical Center in Rotterdam. From 2012 he was trained in hand and wrist surgery at the department of Plastic Surgery for one day a week (Prof. Dr. S.E.R. Hovius). In 2014 he passed the FESSH examination (Federation of European Societies for Surgery of the Hand) with a best diploma award.

Joost lives in The Hague with his wife Petra and their children Carmen and Louise.