New diagnostic and therapeutic possibilities in the treatment of elbow and distal forearm fractures in childhood

PhD THESIS

Marcell Benjámin Varga MD

Department of Traumatology, University of Szeged

, Faculty of Medicine

Doctoral School of Clinical Medicine

Supervisor: Dr. med.habil. Sándor Pintér Ph.D.

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List of publications related to the subject of the thesis

I. Intraoperative sonography may reduce the risk of extensor pollicis longus tendon injury during dorsal entry elastic intramedullary nailing of the radius in children
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II. Ultrasonographic diagnosis of distal paediatric forearm fractures
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List of abbreviations in the text

US	ultrasound
PoCUS:	point of care ultrasound
MSK-US:	musculoskeletal ultrasound
IOP-US	intraoperative ultrasound
PE	pulled elbow
EPL	extensor pollicis longus tendon
LH	lipohemarthrosis
FPS	fat pad sign
eFPS	elevated fat pad sign
ED	emergency department
MHz	megahertz
SCH fracture	supracondylar humeral fracture
SFE	synovial fringe enlargement

I. Introduction

Fractures of the elbow and distal forearm are among the most frequent injuries in children. The spectrum of these injuries is very wide from small contusions without clinical consequences to severely displaced fractures with limb threatening conditions. Primary diagnosis and treatment are often performed by emergency physicians, general practitioners or paediatric surgeons. Indications of unnecessary imaging procedures, under- and over-treatment may occur by less-specialised healthcare personnel. Recognizing certain elbow fractures may be a challenge even for an experienced orthopaedic surgeon due to the special characteristics of childhood. Certain distal forearm and elbow fractures may not be detected by conventional X-rays. The evaluation of severely displaced distal radius fractures and setting up a plan for further treatment may be particularly difficult due to the lack of therapeutic consensus. In recent years, there have been a growing evidence that musculoskeletal ultrasound (MSK-US) can increase the effectiveness of diagnostics and may reduce the number of unnecessary X-rays. Elastic intramedullary nailing of displaced distal radius fractures may have many advantages over traditional percutaneous pinning techniques. Intra-operative musculoskeletal sonography (IoP MSK- US) can further increase the safety of these interventions.

II. Aims of the thesis

The aim was to prove the efficacy of a standardised five-point sonographic screening method of paediatric elbow fractures. US examinations were executed by orthopaedic surgeons in an emergency trauma centre.

In a prospective diagnostic study, we investigated a standardised two-point method in the differential diagnosis of paediatric pulled elbow. We developed an objective, point of care imaging method for confirming or ruling out PE.

We aimed to prove the diagnostic effectivity of ultrasound in distal paediatric forearm fractures in a prospective, two-centred study with large number of patients. Examinations were executed by orthopaedic and paediatric surgeons.

We also aimed to investigate the diagnostic difference of US in radial fractures with different clinical consequences.

We have developed a new operative method for severely displaced distal paediatric radial fractures. In our retrospective study we analysed the results of our technique, which is a stable, physis sparing osteosynthesis with a reduced period of necessary cast immobilization.

We introduced a new ultrasound-assisted intraoperative aiming method for the ESIN technique of paediatric radius fractures. The aim of the procedure was to reduce the risk of EPL tendon injury during dorsal entry elastic nailing. This was an observational diagnostic study.

III. Patients and methods

III.1. Sonographic diagnosis of elbow fractures

Between January 2016 and August 2017 365 children (age 1-14) were enrolled in our study. Point of care US was carried out as a part of the primary physical survey. US examinations were executed by a properly trained orthopaedic trauma resident and two orthopaedic surgeons. US pictures made by high-frequency linear probes.
(Zonare ZS3 Ultrasound System, Mindray®, L20-5W and L-14-5W linear array transducers)
We used a standardized protocol, which included five longitudinal sonographic planes.
Immediately afterwards we made two plane X-rays from the affected side according to protocol. At children whose primary X-rays were negative and/or any of the US planes showed positive findings, radiography was repeated after 4 weeks of injury. The fracture was considered occult, if we detected callus formation. Images which have not met with standard requirements were excluded.US pictures and X-ray results were analysed and compared. The radiologist was clinically blinded to any other patent related information. Interrater agreement by Cohen's chance corrected kappa statistics of sonographic fat pad sign and cortical plane abnormality was calculated between the examiners and a radiologist. We used GraphPad QuickCals® program to calculate the degree of agreement with Kappa.

We also estimated the rate of match of the presumed and final diagnosis. Presence of pathologic sonographic fat pad sign and the cortical plane abnormality were also evaluated separately and together. We used MEDCALC® diagnostic test evaluation calculator to determine the specificity, sensitivity, positive and negative predictive values.

II.2. Sonographic diagnosis of pulled elbow

Between October 2016 and November 2017 205 children were examined with the clinical suspect of PE. (Mean age: 2.3 years). Inclusion criteria were the typical clinical sign of PE: painful, motionless, extended or slightly flexed and pronated arm following a traumatic event under the age of six. A two-plane point of care US examination was carried out at each patient immediately after history taking and primary physical survey. Examinations were done by two orthopaedic surgeons, and a properly trained orthopaedic resident in training.

US pictures were made by high-frequency linear probes. (Zonare ZS3 Ultrasound System, Mindray®, L15-5W and L20-5W linear array transducers)

Imaging included a standard longitudinal central dorsal plane over the olecranon fossa and a longitudinal ventral plane over the radiocapitellar joint.

Painless movement of the affected extremity within 15 minutes with or without a palpable click was considered as successful reduction manoeuvre and confirmation of the diagnosis. Patients with positive FPS and/or further pain and restriction of the movement were X-rayed and immobilized in an open plaster cast or brace. If symptoms have not ceased after 3-5 days, immobilization time was prolonged and elbow X-rays were repeated in the 3rd week after injury. Fracture positivity on X-rays or callus formation on the 3rd week radiographs ruled out PE.

US pictures were saved and analysed by a radiologist who was blinded to any patient-related clinical information. Interrater agreements between the radiologist and the clinicians evaluating the eFPS and the SFE were calculated.

We used Cohen’s chance corrected kappa for calculation. We used GraphPad QuickCals® program to calculate the degree of agreement with Kappa. We used MEDCALC® diagnostic test evaluation calculator to determine the specificity, sensitivity, positive and negative predictive values of the two parameters both separately and together. We also estimated the rate of match of the presumed and final diagnosis.

III.3. Sonographic diagnosis of distal forearm fractures

Between 2011 December and 2015 December 467 children (age 1-14) were enrolled in our study. Patients with isolated and closed distal forearm injury who needed standard two-plane wrist X-rays were included. Point of care US was carried out as a part of the primary physical survey. US examinations were executed by six properly trained doctors. We used a standardized protocol, which included six longitudinal sonographic planes.
US pictures were made by high-frequency linear probes.
(Zonare ZS3 Ultrasound System, Mindray®, L15-5W and L20-5W linear array transducers) Pictures were saved for further analyses. Immediately afterwards we made two plane X-rays from the affected side according to protocol. US pictures and X-ray results were analysed and compared. We used MEDCALC® diagnostic test evaluation calculator to determine the specificity, sensitivity, positive and negative predictive values.

III.4. Elastic intramedullary nailing of distal radial fractures

We reviewed retrospectively 104 patients who underwent operations due to severely displaced distal forearm or diametaphyseal radial fracture between November 2012 and December 2017. 84 children were treated with short, prebended double elastic nails. 20 patients were treated by single titanium nails and a special end seal. (Depuy®, Synthes®, TEN®, End Cap ®) Indications for surgery included closed fractures with total radial or dorsal displacement and shortening. All children were treated by six surgeons experienced both in the ESIN and percutaneous pinning technique. Standard two-plane X-ray images were made in the postoperative first, 4^{th}, 12^{th} and 24^{th} weeks. Angulation of the radial epiphysis was measured in coronal and sagittal planes.
Nails were removed at 6 to 36 weeks after the operation in general or in local anaesthesia.

III.5. Intraoperative sonography of radial elastic stable intramedullary nailing

We performed examinations on six adult cadavers. EPL and Lister's tubercle was visualized by high frequency (20 MHz) ultrasound imaging. (Zonare ZS3 Ultrasound System, Mindray®, L20-5W linear array transducer)
After sonographic determination of the insertion points, we positioned an elastic nail through Lister's tubercle according to standard dorsal technique. Position of the EPL

relative to the elastic nail was examined from transverse and longitudinal planes. This was followed by preparation of the area and comparing the sonographic and anatomic findings. Following our cadaveric experience, we began using intraoperative ultrasound during elastic nailing of paediatric radial fractures.

Between January 2015 and November 2016, 77 radial fractures were operated by dorsal entry elastic nailing with ultrasonic guidance. Inclusion criteria were children with closed and displaced radial or forearm fractures which were candidates for operative ESIN technique. Patients' age was between 4 and 15 years and had closed and displaced radial or forearm fractures with open growth plates. Procedures were executed by 2 orthopaedic surgeons experienced in ESIN technique and with musculoskeletal US qualifications.

IV. Results

IV.1. Sonographic diagnosis of elbow fractures

Out of the 365 children we identified 165 with positive findings (45, 2%) by primary X-rays.

All fractures or dislocations had at least one positive finding out of the five planes.

112 fractures showed positivity in at least two planes.

Out of the combination fractures 6 showed abnormality in two, one in three planes. Sonographic FPS was negative in one radial condylar, two proximal radial and two medial epicondyle fractures. All these fractures showed positivity in at least one other longitudinal plane.

Cortical abnormality was not observed in 3 medial epicondylar and 24 supracondylar fractures and in the 2 elbow dislocations. All these injuries showed positive FPS in US. Cortical abnormality was observed at least in one plane in all radial condylar, proximal radial and proximal ulnar fractures.

12 children had sonographic FPS positivity without X-ray abnormality**.** Out of these patients 7 had a marked LH positivity, and 5 children showed mildly elevated FPS. The LH positive elbows all showed callus formation on follow-up X-rays. These injuries were considered as occult fractures.

The other five patients with mildly elevated FPS have not showed callus formation and were considered as elbow contusions.

7 other children with primary negative X-rays had cortical abnormality in US without positive FPS. These patients have not showed abnormality on follow up X-rays.

Twelve pseudo-positives findings were identified. No pseudo-negativity was detected using the five examining points.

Evaluating the sonographic dorsal FPS as a sole parameter for fracture detection we found sensitivity: 0, 97, specificity: 0, 97, positive predictive value: 0, 97, negative predictive value: 0, 97.

Evaluating the effectivity of the four cortical planes we calculated sensitivity 0, 85 specificity 0.96 positive predictive value: 0. 95, negative predictive value 0.87.

The overall values of the five planes were the following: specificity0.97 sensitivity 1, positive predictive value 0.97 negative predictive value: 1

Interrater agreements on the cortical plane abnormality were considered good and very good. (Kappa= 0.79, 0, 81, 0, 79)

Agreements on differentiation of eFPS, normal FPS or LH in sonographic pictures were very good in all cases. (Kappa= 0, 83, 0, 86, 0, 82)

Exact identification of the type of the injury only by US was possible in 113 cases. (68%)

IV.2. Sonographic diagnosis of pulled elbow

Out of the 205 children 196 (95,6%) proved to have pulled elbow and 9 (4.39%) fractures.

These latter injuries were type I. SCH fractures by Gartland classification.

Sonographic SFE sign was identifiable in 156(76%) cases. EFPS was negative in all but one PE cases.7 children had type I.SCH fracture which was visible in the first X-rays, and two children had occult fractures, (0.97%) which were proved by the evidence of callus formation on the follow-up X-rays. These children all had positive FPS and negative findings for SFE sign. Interrater agreement between the examiners and the radiologist showed good results in the evaluation of SFE, (0,76,0,74,0,79) whereas excellent (0.939,1,0.939) in the interpretation of FPS.SFE showed 83% sensitivity and 100% specificity, 100% positive predictive value and 18% negative predictive for PE as a sole parameter. Presence of the FPS proved to result 99% sensitivity and 100 % specificity,100% positive predictive value and 90 % negative predictive value.

Evaluating the two parameters together both sensitivity, specificity, NPV and PPV were 100%

IV. 3. Sonographic diagnosis of distal forearm fractures

Out of 467 children we found 270 (57.8%) positive and 197(42.2%) negative results for distal forearm fracture. Sonography has shown 263 positive and 204 negative results. The fractures were divided into three groups based on clinical significance.
Children without the need of further clinical intervention were divided into group I. Injuries which needed only reduction manoeuvre were divided into group II. Unstable severely displaced fractures which needed operative intervention were divided into group III.
We also investigated the distribution of pseudo-negative and pseudo-positive cases in each group.
We considered the results pseudo-negative when sonography has not confirmed the presence of any fractures which were detectable on X-rays. All these results (n=7) were found in group I. Fractures which have been confirmed only by ultrasound were considered as pseudo-positive. Such results (n=7) were found also only in the group I. Based on our results we found sensitivity 0.97 and specificity 0.96 for sonographic fracture detection in the area of distal paediatric forearm.

IV.4. Short elastic intra-medullary nailing of distal forearm fractures

None of the 104 cases required reoperation. Implant migration did not occur. No deep septic complication was observed.
We detected a superficial skin infection at 3 children in the double nailed group. Inflammatory signs have disappeared after the nails had been removed. All fractures have been stably consolidated at the time of nail removal.
9 children had moderate skin irritation caused by the ends of the implants. No skin irritation was observed in children who had end seal protection.
No tendon or nerve injury was found in any of the groups. All but one of the implants were removed between the sixth and twenty-fourth postoperative weeks. In one patient one of the nails was placed too deep (below the level of the cortical bone) so we could not remove it. The average follow-up time was 9 months to 4 years. Each child has

healed with full function, no growth disturbance or movement limitation has developed. Brace treatment required an average of 12 days. (1-4 weeks)

Analysing the X-rays made during the checking times the following results were obtained: In the group whose members were treated by double nailing, anatomic reduction was found in 70 children, good in 13 children and acceptable in 1 child. Out of 20 patients treated by a single elastic nail and End cap 13 showed anatomic and 7 good reductions.

X-rays on the fourth postoperative week showed slightly worse result in the double nailed group: classification was changed from anatomic to good in 4 children, from good to acceptable in three children and 1child has been graded to bad category due to moderate secondary displacement. Children with single nail end End Cap® synthesis have not showed any tendency to secondary displacement.

X-rays made in the 24th postoperative weeks showed anatomic reduction in all but one patient. This latter child showed good (12 degrees of dorsal angulation) reduction after one year, and anatomic reduction after 24 months.

IV.5. Intraoperative sonography of radial elastic stable intramedullary nailing

Ultrasonographic identification of EPL and Lister's tubercle in the transverse view was possible in all children. Determination of the position of the nail to EPL was also possible in all patients. Measured mean distance of the transverse view centre of the EPL and nail was 0.49cm by US. (range: 0.3–0.62cm, SD=0.66). Longitudinal view of EPL was not clearly defined in 2 cases. Based on the sonographic transverse view (insertion points were too close (< 0.3cm) to EPL) the operator decided repositioning the nails by 2 patients. On one occasion EPL movement was not seen with dynamic assessment, although the tendon was clearly identifiable. In this case, we decided rebending the end of the nail. After correction, we were able to identify normal tendon movement. Sonographic procedures took average 5 minutes (range: 2–8 min. mean=4.8min) extra time during operations. We have not found EPL injury or septic complications postoperatively. All patients were followed for at least 12 months after operation. Nails were removed in all children without further complications.

V. Discussion

V.1. Sonographic diagnosis of elbow fractures

Distinction of normal and pathological radiological FPS is not clearly defined. Its presence related to fractures is controversial. Sonographic FPS seems much more specific than radiologic and differs from it. Unambiguously with other studies we think that the absence of abnormal FPS means the real importance which has a strong negative predictive value.

We found five children (1 radial condylar and two radial neck and two medial epicondylar fractures) with initially negative sonographic FPS. This can be since certain fractures do not cause immediate intraarticular bleeding or fluid collection and the elapsed time from the injury can also play a role in elevated fat pad or LH formation. Repeated US on the first week showed that FPS became positive in all fractures. At the same time cortical disruption and angulation were visible in the second (radial condylar fracture) or third (medial epicondylar fractures) sonographic planes so the presence of these fractures would not have been missed.

We have seen seven pseudo positive cases when abnormality was present in the II and III planes. Out of these 6 were in the plane II and one in the plane III. No callus formation or other abnormality was confirmed at these children and complains disappeared at the latest in two weeks. Small disruptions were observed in the osteochondral line in these cases, which we think anatomic variations or small infractions without clinical consequences.

Radial condylar, proximal radial and proximal ulnar fractures all showed positivity in the corresponding planes thus these injuries can be detected even without the FPS.

Abnormality in the plane II-III. was less specific in medial epicondylar and supracondylar fractures, especially if these injuries are without displacement. X-rays of these fractures show also very subtle findings. Several fractures with less clinical significance have not showed any cortical abnormality by US, but all showed FPS positivity so wold not have been missed.

The four cortical sonographic planes without plane I. showed abnormality in 87% in all fractures. Evaluating the cortical views and the FPS together the specificity increased to 0, 99 and sensitivity to 1, so using the five planes in a 90-degree bent position of the elbow seems to be enough. Exact identification of the fracture types was possible in 68%.

Summarizing our result, we conclude that US is an effective tool in the screening of paediatric elbow fractures. Using additional longitudinal planes is more effective than the evaluation of the sonographic fat pad sign as a sole parameter. US may be enough as a definitive diagnostic tool in negative cases. US is a very useful imaging modality to detect occult fractures, and bony injuries without displacements, and in certain cases could be used instead of X-rays.

V.2. Sonographic diagnosis of pulled elbow

With our combined two-point sonographic planes we both searched signs of PE and fractures. According to several studies the most reliable and reproducible sonographic sign of PE is the presence of synovial fringe enlargement. (SFE) Success of the reduction can be checked by its disappearance. PE usually does not show fat pad abnormality which is a sign of intraarticular fluid accumulation caused rather by fractures or forceful contusions. Sonographic fat pad sign is more sensitive than radiological, even 1-3ml intraarticular fluid accumulation can cause an elevation of the posterior border of the pad in the olecranon fossa. Although we found one study in the literature which reported sonographic elevated fat pad sign or lipohaemarthros in 8 radial head subluxations out of 42 children in our series we experienced these phenomena only in one case out of the 196 PE. The other 195 children with confirmed PE all showed normal FPS whereas the other 9 cases with eFPS or LH all proved to have supracondylar humerus fractures and no SFE positivity. We consider it possible that PE which is unreduced more than 6-8 hours may cause intraarticular fluid accumulation and elevated FPS. Based only by the physical findings we found 9 cases (4.39 %) which were thought to be PE by our examiners and proved to be fractures by imaging modalities.

V.3. Sonographic diagnosis of distal forearm fractures

Ultrasonic diagnostics of distal forearm fractures is made possible by the characteristic injuries affecting this area. Children with open growth plates and under the age of fourteen rarely have irregular and displaced intraarticular fractures. Paediatric distal metaphyseal or epiphyseal injuries show typical patterns, which can be visualizable by the sonographic mapping of the bony cortex. The six standard planes used in our clinical practice proved to be enough to determine the presence or type of a fracture.

Out of the seven children who were considered as pseudo-positive four had prolonged pain in the area if the wrist. Although the reference X-rays were negative, the presence of a cortical crease of the affected side was clear in US, when we compared it with the healthy side. We think, these children had occult fractures.

The pseudo-negative cases were observed in the initial part of the study, so we suppose this error were due to the “learning curve” period.

In the group two we classified injuries which needed reduction and plaster cast immobilization but no operative interventions. These were mostly angulated greenstick fractures or epiphyseolysis with displacements. We have not observed difference between the diagnostic efficiency of US and X-rays.

The exact evaluation of unstable fractures with shortening and severe displacement was more difficult. Although there were no pseudo-negative cases in this group, the determination of exact fracture pattern was not possible only by US. In these cases, sonography is useful only as a screening modality to confirm the presence of a fracture which need operative intervention.

V.4. Short elastic intra-medullary nailing of distal forearm fractures

The short double nailing technique is a modification of the classic ESIN method. The main difference is the length and the pre-contoured curve of the nails. The 2 nails ensure a long contact area with the inner cortex, which is mandatory for axial stability. We hypothesize that "short" ESIN nails inserted at the distal metaphyseal area work the same way as conventional ESIN in a shaft fracture.

The insertion points (Lister tubercle and radial dorsal side of the radius) are the well-known insertion places of conventional radial ESIN nails. Both areas are located proximally to the physeal plate thus an iatrogenic growth plate injury can be prevented.

The insertion of a second nail becomes obsolete in the mono-elastic nailing technique because rotatory stability is given by the End Cap® implant. End Cap® also protects soft tissues. Using one nail reduces the risk of the two insertion points but needs a wider incision because tendons should be carefully protracted due to the size of the End Cap® implant.

By the end of the follow-up, all X-rays showed anatomical reduction. We have not observed any growth disturbances.

V.5. Intra-operative sonography of radial elastic stable intramedullary nailing

EPL injuries found in the literature are related to dorsal entry elastic nailing, it seems to be a unique complication of this approach. Reviewing the literature and our experiences we concluded that optimization of the insertion points and the position of the extraosseal end of the nails can reduce the risk of both acute and chronic ruptures. Intraoperative ultrasound has been proven an easy and useful tool for visualizing these optimal reference points. We

found that exact sonographic differentiation of Lister's eminence and transverse view of EPLT were easily feasible. The visualization of the end of the nail, and the determination of its position to Lister's eminence and tendon during insertion is more difficult and technically demanding. Despite this latter fact using sonographic guidance took an average extra 5 minutes during operations. Two times the longitudinal views of tendons were not clearly identifiable. We think this was rather a technical problem in the early learning curve period.

VI. Conclusions

US is an effective diagnostic modality in the screening of distal paediatric forearm fractures.

US shows the same diagnostic efficacy as X-rays in the exact identification of fractures without displacements and angulated greenstick fractures.

Occult radius torus fractures in children may be detected more accurately by US.

US can detect unstable and severely displaced distal forearm fractures, but X-rays are mandatory for exact fracture identification and therapeutic plan.

Paediatric elbow fractures can be screened by point of care ultrasound

Using five standardized US planes increases the diagnostic efficacy of paediatric elbow fractures.

Occult paediatric elbow fractures can be detected by US

In younger children US may give more accurate information about the exact nature of the fracture than X-rays.

The differential diagnosis of pulled elbow can be safely confirmed by a standardized two-planes US method.

Short intramedullary elastic nailing may be an alternative to percutaneous pinning in the treatment of severely displaced paediatric distal metaphyseal fractures.

Using short intramedullary nailing in distal paediatric forearm fractures there is a need only a short cast for one or two weeks postoperatively.

Intraoperative sonography may reduce the risk of extensor pollicis longus tendon injury during dorsal entry elastic intramedullary nailing of the distal radius.