RESEARCH ARTICLE

Preoperative Three-Dimensional Planning of Screw Length is not Reliable in Osteotomies of the Humerus and Forearm

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Abstract

Objectives: Pediatric upper extremity fractures are seen frequently and sometimes lead to malunion. Three-dimensional (3D) surgery planning is an innovative addition to surgical treatment for the correction of post-traumatic arm deformities. The detailed planning in three dimensions allows for optimization of correction and provides planning of the exact osteotomies which include the advised material for correction and fixation. However, no literature is available on the precision of this computerized sizing of implants and screws. This study aimed to investigate the differences between 3D planned and surgically implanted screws in patients with a corrective osteotomy of the arm.

Methods: Planned and implanted screw lengths were evaluated in patients who underwent a 3D planned corrective osteotomy of the humerus or forearm using patient-specific 3D printed drill- and sawblade guides. Postoperative information on implanted hardware was compared to the original planned screw lengths mentioned in the 3D planned surgery reports.

Results: Of the 159 included screws in 17 patients, 45% differed >1 mm from the planned length (P<0.001). Aberrant screws in the radius and ulna were often longer, while those in the humerus were often shorter. Most aberrant screws were seen in the proximity of the elbow joint.

Conclusion: This study showed that 3D-planned screws in corrective osteotomies of the humerus and forearm differ significantly from screw lengths used during surgery. This illustrates that surgeons should be cautious when performing osteotomies with 3D techniques and predefined screw sizes.

Level of evidence: IV

Keywords: Osteotomy, Patient-specific planning, Screw length, Surgical guides, Three-dimensional

Introduction

Fractures of the upper extremity are very common injuries children.[1-3] With an incidence of 23% to 31%, a forearm fracture is most frequently seen.[4] The incidence of supracondylar humerus fractures in children is reported to be between 3.3% and 16.6%.[5] It is important to realize that a fracture might seem to heal in an acceptable way at first. However, it is possible that, during growth, deformations develop due to malunion caused by insufficient reduction or fixation of the fracture. This can result in disability in daily life,[6] sometimes arising not until adolescence or adulthood. Malunion of both humerus and forearm fractures may involve deformities in one, two or three planes.[7,8] Ultimately, this may result in pain, insufficiency of the lateral collateral ligament,[9] rotational impairment,[8] asymmetrical loading of the cartilage resulting in chondral damage and finally posttraumatic osteoarthritic modifications.[10]

In order to obtain an adequate alignment and improvement of the limb's function, a corrective osteotomy may be indicated in selective cases. However, these

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surgeries are technically demanding procedures. Hence complications such as residual deformity, delayed or nonunion and neurovascular injury are described.[8,11]

Over the past decade, the use of pre-operative three-dimensional (3D) planning has increased. Patient-specific 3D surgical guides created by using computed tomography (CT)-scans can be a helpful tool to correct the malunion in multiple planes.[12] To create a 3D-image, bilateral CT-scans are made. The scan of the affected side is digitally placed over a mirrored scan of the contralateral side. Next, the required correction to match the non-affected side is calculated. The software uses landmarks on both the affected and contralateral side to line up the scans, taking the variability of the morphology in consideration.[13] Using this data, 3D surgical guides with slits for the sawblades and holes to predrill the screws are designed and printed out of polyamide resin. During the work-up to surgery, engineers and surgeons team up to obtain a plan that allows the most efficient osteotomy using a safe surgical approach. During the surgical procedure, the guide is placed directly onto the affected bone. A sterilized 3D-printed 1:1 model of the CT-scan is thereby available to the surgeon, which allows tactile feedback and an option to compare guide placement to the planned position. These patient-specific guides ensure that free-handed osteotomies are no longer necessary. As a result, com-plications such as residual deformity that are seen in traditional osteotomies are diminished.[13,14] Furthermore, the surgery duration and difficulty level are reduced.[15] Moreover, the guide for the sawblades enables the surgeon to create an isosceles triangle more easily, allowing for optimal osseous contact that supports the healing process.[16]

Three-dimensional planning and surgical guides also assist in the implantation of plates and screws for fixation of the osteotomy, which may improve precision. However, incorrect placement of screws or a wrong size of screws can potentially lead to irritation and rupture of tendons when screws are too long,[17] less rigid fixation when screws are too short,[18] damage of the growth plate or articular cartilage[19] in case of penetration of screws into the joint[16] and suboptimal correction of the osteotomy.[20] Thus, - precise placement and sizing of the screws are crucial to the outcome.

Hypothetically, screw length should match exactly to the preoperative planning in order to achieve adequate plate fixation following the 3D-planned corrective osteotomy using a patient-specific guide. However, based on our experiences, we hypothesized that the preoperative planning of screw length may not be followed accurately and that there could be a discrepancy between planned and implanted screws. Insight in the relation between implanted screws and the planned length may aid in optimizing the 3D-planning technique. Therefore, this study aimed to assess the implanted screw lengths in 3D-planned corrective osteotomies of the humerus and forearm with respect to the preoperatively planned sizes.

Materials and Methods

Patients

In this retrospective study, 17 consecutive patients, with a median fracture age of 10 years (range 3–49) and with a median age of 18 (range 11-51) at the time of surgery, that had 3D-planned corrective surgery of the ulna, radius, and/or humerus in two large teaching hospitals in Northern Europe were included from January 2009 to September 2020 with a minimum follow-up of 1 year. This study was approved by the local research committee of the Amphia Hospital on 12 October 2021 and the NoordWest Ziekenhuisgroep on 21 December 2021. On 10 November 2021 the local Medical ethics review committee approved this study. Informed consent was obtained from all patients regarding the use of data from the patient files. The data was anonymized. Patients were excluded if they declined participation and if more than two implanted screw lengths could not be identified. The primary outcome measurement was the length of the implanted screws as related to the planned screw length.

3D-planning

All surgical plans and 3D-printed guides were provided by Materialise (Belgium) and were made in consultation with the treating surgeon. A CT-scan (Siemens SO-MATOM® Edge Plus and SOMATOM® Definition AS) was obtained from both arms with a slice thickness of 0.6 mm. The CT-scan of the contralateral side was mirrored and digitally placed over the affected side with use of the Materialise software Mimics inPrint. The software calculated the required correction in the deformed arm compared to the non-affected side. This data was then used to create a patient-specific polyamide 3D-surgical guide. The guides had slits for the sawblades and holes to predrill the screws. They fitted tightly on the morphology of the patient's bone and were temporarily fixated with K-wire to prevent movement.[21] To provide the surgeon with a better impression of how to fit the guides on the bone in the patient, a 1:1 printed model of the patient's bone was supplied. For all patients in this study, the patient-specific surgery plan was provided [Figure 1]. From this plan, data could be extracted regarding the 3D bone image, the descriptions and specifications of the surgery guide, and the step-by-step instructions on how to execute the procedure.

Surgery and hardware

Three experienced orthopedic surgeons from the Amphia Hospital in Breda, the Noordwest Clinics in Alkmaar and the Erasmus Medical Centre in Rotterdam performed all surgeries. Naturally, they were not blinded to the preoperative plan.

The patient-specific surgery plan included a detailed description of the instruments and materials required during surgery. It contained information on precise screw lengths, type of screws (locking or non-locking), screw locations, and screw placement order (see figure 1). Patient files were investigated to obtain information on the types and length of screws that were used. Non-calibrated postoperative X-rays that were made following the care-as-usual protocol were used to determine if the order of screw length corresponded with the location mentioned in the 3D-plan. This was done by measuring the length on a postoperative digital X-ray. The measurements were done by MB (first author) who was not blinded for the preoperatively planned screw lengths.

The screws that were used during surgery had 2 mm increments. The minimal possible deviation therefore ranges from 0 mm (both planned and implanted screws had the same length) to a maximal possible deviation of 1 mm. All the differences of more than 1 mm were therefore defined as aberrant and an actual deviation from the plan.

Figure 1. Example of 3D planning of a distal humeral correction osteotomy. From left to right: a screw hole drill guide, a sawblade guide and planned plate and screws

Statistical analysis

The data was processed using the program SPSS version 27.0 (SPSS, Chicago, IL). Normality was assessed using the Shapiro Wilk test. A Wilcoxon signed rank test was used to statistically analyze differences between the planned and implanted screw lengths per bone, and for all the patients together as one group, respectively. For each analysis, significance was determined at P<0.05. If there were one or two not-identifiable screw lengths, these screws were excluded from the analysis. When more data on screw length was missing, the patient was excluded from the study.

Results

Patients

Seventeen patients (25 bones) met the inclusion criteria and were included, with a median fracture age of 10 years (range 3–49) [Table 1]. The median follow-up was 1 year and 11 months (range 1-6 years). The indications for surgery were complaints (such as pain or limited range of motion) due to malalignment of the affected bone in all cases. In all but one case the malalignment was caused by a previous fracture. In the upper-arm group, all of the previous fractures were supracondylar humerus fractures. In the forearm group, there were two cases with a fracture involving only the radius; one distal radius fracture and one midshaft fracture. Furthermore, there were eight both-bone fractures in the forearm group and one case where malalignment was due to pathological bowing (case 16).

Screw length comparison

In total, 159 (51 upper arm, 108 forearm) planned and implanted screws were included in 25 bones. In total, there were 86 implanted screws longer than planned, 58 screws shorter than planned and 15 screws the exact planned length. Seventy-one (45%) of the implanted screws differed >1 mm from the planned length. The screws in the upper arm group and the forearm group did not follow a normal distribution (P<0.001; Shapiro Wilk test). There was a significant difference between planned and implanted length (P<0.001; Wilcoxon signed rank test).

Humerus screw analysis

When analyzing the screw lengths in the humerus group, we found a median of 27 mm (range 14-58 mm) in the 3D planned screws and a median of 30 mm (range 14-60 mm) in the implanted screws. Most of the aberrant screws were shorter than planned [Table 2], and aberrant screws were more frequently seen distal to the osteotomy. There was no significant difference in the humerus group when analyzing the planned and implanted screw lengths in the entire upper arm group (P =0.854).

Forearm screw analysis

In the radius group, there was a median of 15 mm (range 12-26 mm) in the 3D planned screws, and a median of 16 mm (range 14-24 mm) in in the implanted screws. A significant difference was seen (P <0.001) between the planned and implanted screws. Most of the screws were longer than planned and aberrant screws were equally seen distally and proximally to the osteotomy (see table 2).

When analyzing the screws in the ulna group, we found a median of 14.8 mm (range 12-32) in the 3D planned screws and a median of 16.0 mm (range 14-30 mm) in the implanted screws. A significant length difference (P = 0.002) was found between the planned and implanted screws. Most of the screws were longer than planned, and aberrant screws were mostly seen proximal to the osteotomy (see table 2).

Table 1. Patient characteristics

Case	Age at fracture (years)	Age at surgery (years)	Gender	Side	Malunited bone	Number of included screws	Follow-up (years)
1	8	19	F	R	humerus	7	3
2	7	14	M	R	humerus	7	6
3	14	16	F	R	humerus	8	6
4	7	11	M	R	humerus	8	1
5	8	22	F	L	humerus	7	1
6	3	22	M	L	humerus	14	1
7	11	14	F	L	radius	7	3
8	49	51	F	R	radius	5	1
9	6	17	M	L	radius, ulna	14	1
10	8	19	F	R	radius, ulna	11	1
11	N/A	18	M	R	radius, ulna	12	2
12	13	20	F	R	radius, ulna	12	2
13	12	24	F	L	radius, ulna	8	4
14	10	15	F	R	radius, ulna	10	1
15	30	32	M	R	radius, ulna	6	1
16	N/A	16	M	L	radius, ulna	11	6
17	10	17	F	R	radius, ulna	12	1
Median	10	18	....	.....	....	8	1

F: female, M: male, R: right, L: left, N/A: not available

Table 2. Length of planned and implanted screws and numbers of screws with >1 mm difference between the planned and implanted lengths

	3D-planned screws (median mm and range)	Implanted screws (median mm and range)	Difference between planned and implanted length	Longer than planned (>1 mm)	Shorter than planned (>1 mm)	The same length as planned
Humerus	27 (14-58)	30 (14-60)	P= 0.854	----------------	----------------	----------------
Distal to osteotomy	----------------	----------------	----------------	6 (35%)	10 (59%)	1 (6%)
Proximal to osteotomy	----------------	----------------	----------------	3 (50%)	2 (33%)	1 (17%)
Radius	15 (12-26)	16 (14-24)	P<0.001	----------------	----------------	----------------
Distal to osteotomy	----------------	----------------	----------------	9 (75%)	0 (0%)	3 (25%)
Proximal to osteotomy	----------------	----------------	----------------	9 (70%)	0 (0%)	4 (30%)
Ulna	14.8 (12- 32)	16 (14-30)	P= 0.002	----------------	----------------	----------------
Distal to osteotomy	----------------	----------------	----------------	10 (67%)	3 (20%)	2 (13%)
Proximal to osteotomy	----------------	----------------	----------------	16 (73%)	2 (9%)	4 (18%)

Discussion

To the best of our knowledge, this is the first study that investigates the accuracy of 3D-planned screw lengths in corrective osteotomies of the upper extremity. Despite the meticulous 3D planning, almost all cases showed discrepancies between the planned and implanted screw lengths (*P<0.001*). This could potentially lead to irritation of soft tissue, growth plate or articular cartilage when screws are too long, or less rigid fixation when screws are too short.

In a sub-analysis of the affected bones, a significant difference in planned versus implanted screw length was seen in the radius (*P <0.001*) and ulna (*P = 0.002*). In the forearm, most aberrant screws were longer than planned. In the humerus, most aberrant screws were shorter, especially distal to the osteotomy, although not statistically significant.

An interesting finding was that more deviation from the planned length was observed in the proximity of the elbow joint, both in the humerus and ulna. An explanation for this finding could be related to the intricate morphology in this region. The curved bony anatomy in the proximity of the epicondyles, the olecranon and processus coronoideus could cause more difficulty to plan the right length and also cause more deviation when the guide is not placed exactly as planned. Another finding that could be explained by morphology is that most cases with screw length differences were seen in the ulna group. This may be caused by the rather oval shape of the ulna and the lack of prominent ridges (and thus fewer anatomical landmarks), which impedes correct guide placement.[20,22] Evaluating the postoperative details of the osteotomy and the exact positioning of the implanted plate would require a postoperative CT-scan. In the included cases, a radiograph was taken postoperatively following the care-as-usual protocol of each hospital. None of the included patients had clinical signs of malrotation or complications that would have required a postoperative CT-scan. Therefore, no post-operative CT-scans, which available and hence it was not possible to compare the position of the implanted plate to the 3D-planned images. Nonetheless, the placement of the guides was examined during surgery by comparing it to the placement of sterile 3D-printed models of the CT-scans that are available to the surgeon peroperatively. The placement of the plate and screws was examined using fluoroscopy during surgery. One prospective study that incorporated postoperative imaging, examined the angle of deformity in pre- and postoperative X-rays and found that this angle decreased significantly.[13] However, this study did not compare the exact placement of the plate and screws in relation to the 3D-plan. Future prospective studies should incorporate post-operative CT-scans to evaluate if the placement of the plate and screws is the same as stated in the preoperative 3D-plan. Comparing a postoperative CT-scan of the affected arm with the contralateral side and the 3D corrected version of the affected side could reveal if the planned angulation and correction of the bone is achieved, which could lead to further improvement of the 3D-planning technique.

A possible factor that could influence the accuracy of the 3D-printed guides and therefore the outcome of the surgery is the time between the CT-scan and surgery because of growth. To minimize the differences between the CT scan and the real bone, a maximum of 6 months between the CT and surgery is advised, preferably for all patients. The expectation is that, in younger children with rapid growth, more often an underestimation of screw length is seen. The number of included cases in the present study was too small to make a statistical statement and correlate time between CT and surgery with deviation in screw length. Future research is needed to find out if time between the preoperative CT-scan and surgery is of influence on the fitting of the surgical guide and therefore on the planned length of the screws as well as clinical outcomes.

There are some studies on 3D-planning for fixation of fractures of the upper extremity that mention screw length.[23-25] for example, one study concluded that 3D planned osteosynthesis in fractures of the distal radius results in more screws with an accurate length.[25] Another study that, among other things, reviewed screw length in computer assisted virtual preoperative planning of the fixation of proximal humerus fractures, found that implanted screw lengths differed the most in the proximal region of the humerus in relation to the planned length.[23] This corresponds with our finding that most aberrant screws were seen in proximity of a joint. Furthermore, there are studies that evaluated the direction of the screws in 3D-planned osteotomies.[20,22] However, no study on difference in length between planned and implanted screws in 3D planned corrective osteotomies of the humerus, radius or ulna has been executed so far, therefore it is not possible to make a one-to-one comparison with previous similar studies.

There were a few limitations to this study. Firstly, this study did not contain data on clinical outcome. There was not enough clinical data on, for example, range of motion, complications and age to include in a statistical analysis. Patient-reported outcome measures (PROMs) were not obtained routinely. Therefore it was not possible to establish a correlation between clinical outcome and the amount of deviating screws. There was no opportunity to expand the data on clinical information since the design of this study was retrospective. Secondly, confirmation bias could have occurred since the length of the implanted screws was manually determined by the author. Finally, the study group was small. However, despite this fact, clear observations were made regarding the percentage of deviating screws and locations of deviation.

Conclusion

The use of 3D-planning and 3D-printed guides is a safe and effective way to make corrective osteotomies in multiple planes less complicated, create optimal osseous contact and reduce the surgery time and residual deformity. However, in this study, we found that the planned screw lengths differed significantly from the implanted length. Surgeons often used a different length based on their visual findings and depth measurements during surgery. In proximity of the elbow joint, most screws differed from the plan; it is hence advisable to take extra notice when placing screws in this region and to not solely rely on the advised screw lengths. Additional research is needed to establish the cause of the found discrepancy and to assess if this leads to clinical consequences to further optimize this promising surgical 3D technique.

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Authors Contribution:

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Lisette Langenberg: data collection, supervision, review, editing

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