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Corrective osteotomies at the distal humerus and forearm: a practical review

Introduction

The elbow and forearm are equally complex anatomical and functional units with a unique osseous, soft tissue, and articular composition that also form an ingenious functional entity [1, 2]. Disruption of this complex biological relationship, either through posttraumatic or hereditary changes, can have a significant impact on the functional system of the upper extremity, leading to pain, instability in both the proximal and/or distal radioulnar articulation, and reduced range of forearm motion. Corrective osteotomy for malunited fractures or hereditary deformities of the upper extremity, especially in the distal humerus and proximal forearm, are challenging procedures and should be performed in specialized centers. This practical review discusses: the essential aspects of the pathoanotomy of the main posttraumatic conditions, their clinical and radiological assessment, the pathway from preoperative planning to actual deformity correction surgery, either with one-stage correction or using external fixation devices, and finally the functional outcome one can expect for these patients. This is a practical review and cannot give a comprehensive overview of all deformities and operative techniques in the specialist's armamentarium.

Examining the patient, analyzing the deformity, and informed consent

Posttraumatic elbow and forearm deformity can occur after either non-operative or operative treatment of acute fractures, as well as following deformity correction surgery (iatrogenic); it presents as impairment of function that is often exacerbated during growth [1]. While the most common deformity at the elbow, varus deformity, was seen for many years as a "purely" cosmetic problem, recent publications and the observation in the authors' multidisciplinary group from Hamburg, Düsseldorf, and Markgröningen, Germany, have shown that longstanding varus deformity of the elbow can lead to ulnar neuritis, medial instability, and functional impairment of the affected upper extremity [3–7]. Nonunion of the radial or ulnar condyle leads to severe arthrosis of the affected elbow joint, resulting in pain, loss of motion, and handicap in daily life and professional activities [8]. Chronic missed Monteggia deformity inevitably results in loss of flexion, forearm rotation, and arthritic deformity of the radiocapitellar joint [9–14]. In all cases, clinical history may reveal pain, stiffness, loss of motion, loss of strength, disability, and visible cosmetic changes. Painful limitation of the elbow is due to malunion in the frontal sagittal and coronal plane (often multiplanar), as well as to painful instability in, e.g., epicondylar nonunion of partial necrosis of the capitulum or trochlea (**Fig. 1**). Limited forearm rotation may be related to bony impingement and tensioning of the intraosseous membrane (IOM) secondary to angular deformity (**Fig. 2**; [2, 3, 9]). It may also occur due to abnormal joint kinematics following radioulnar joint malalignment secondary to axial malunion.

Clinical examination should investigate and objectively record the restriction in range of elbow and forearm motion (neutral-0-method), particularly pronation and supination, and determine signs of proximal radioulnar joint (PRUJ) and distal radioulnar joint (DRUJ) instability and pain with and without movement or strenuous exercise. Painful clicking at both the elbow and wrist joint during pro- and supination, hard or weak stopping of motion (often with a visible and palpable subluxation of the joint complex, especially at the elbow), as well as motion and stability of both the wrist and elbow joint are documented. The elbow axis is documented both clinically and radiologically by measuring the humerus-elbow-wrist angle, the Baumann angle, and the carrying angle (**Fig. 3**; [15–17]). Information about hobbies, daily restrictions

Fig. 1 ▲ Anteroposterior X-ray of the right elbow of a 20-year-old patient with a neglected fracture of the ulnar epicondyle (and trochlea anlage) as a child. He presented with varus malalignment, ulnar instability, and severe pain

Fig. 2 ▲ Three-dimensional reconstruction of the right forearm of a 14-year-old boy with severe forearm deformity due to multiple osteochondroma. Note the severe shortening and bowing of both forearms, the protuberant tumors on both distal forearm bones, and the high radial articular angle leading to an advanced carpal slip. Neither forearm rotation nor radial abduction is possible

caused by the condition, pain medication use, ability to perform physical exercises, and the importance of having a "normal-looking" forearm (the cosmetic aspects) should already be recorded at an early stage. The vascular and neurological status, previous scars, as well as a history of previous infection and skin changes should be documented. In the case of neurological impairment, nerve conduction assessment is mandatory, even in children and adolescents. The authors recommend including a patient-related outcome instrument prospectively in the assessment protocol of both posttraumatic and hereditary deformity management; they use the validated Norwegian, German, and Dutch disabilities of the arm, shoulder, and hand (DASH) questionnaire preoperatively, at 3 months, and at 1 year [1]. The minimal clinically relevant difference in the DASH in younger patients and adults has been estimated to be 10 points. Another important aspect of the preoperative assessment should focus on: information about possible complications; the clinical outcome with conservative (non-operative) treatment vs. operative intervention and the need for subsequent surgery (possible second-stage correction in the same or other region); the expected functional outcome and scope of improvement; and, finally, an evaluation of compliance of the patient and the family. This also has a profound impact on the treatment concept used—some patients are better served by a one-step correction than a long-lasting gradual correction of a complex deformity with a complex external ring fixator system. In all corrective cases, a structured treatment plan is formulated and discussed preoperatively according to Paley's principals in complex corrections, namely, diagnosis, clinical features, problems, obstacles, and equipment required [1]. Additional measurements at the distal forearm and wrist, such as carpal slip, radial bow, radial articular angle, among others, are performed where necessary; these are described in detail elsewhere [3].

In the last 5 years, in cases of complex deformities in more than one plane at the distal humerus, as well as in cases with rotational deformity in the forearm (e.g., after malunion), the authors perform computerized three-dimensional (3D) planning with/without patient-specific templates, since rotational deformities cannot consistently and accurately be calculated by traditional planning techniques [1, 9, 16, 19].

Principals of correcting distal humeral deformity

Cubitus varus or valgus is a deformity following a fracture of the elbow in children. Cubitus varus is widely recognized as a result of malunion of supracondylar fractures, while cubitus valgus can result from malunion or nonunion of lateral condylar fractures [20]. The principal complaints are cosmetic (simple deformity in the frontal plane), loss of function (limitation in the flexion extension arc in deformities in the sagittal plane), and instability/ulnar nerve problems (cubitus valgus).

Although cubitus varus has been regarded as a purely cosmetic problem (and the authors do not perform cosmetic corrections) in the pediatric population for severely years, symptomatic elbow instability and resulting ulnar neuropathy from the mechanical axis malalignment are common and a clear handicap in adults (◘ **Fig. 4**). Disruption of the biomechanical axis leads to soft tissue (tardy posterolateral rotatory instability) and morphologic bony alterations (arthritic changes) in the elbow and offers a compelling argument for early corrective osteotomy to treat pediatric cubitus varus [5]. Four different surgical techniques are currently available for the correction of cubitus varus in children, adolescents, and adults: lateral closing-wedge osteotomy, step-cut osteotomy, dome osteotomy, and multiplanar osteotomy (◘ **Fig. 5**; [6]).

Although the lateral closing-wedge osteotomy is burdened with a prominent lateral condyle prominence (LCP), a recent systematic review by Solfelt et al. in altogether 894 children comparing the aforementioned surgical techniques, the overall meta-analytical summary estimate for the total rate of good to excellent results was 88%; no technique significantly affected the surgical outcome or was safer/more effective than another method and, importantly for informed consent counseling, the overall risk of complications was 15%. Nerve palsies occurred in less than 3% of cases and 75% of these were transient [4]. In younger children (>11 years of age), and whenever possible, the authors perform a closing wedge osteotomy with k-wires, in older children, adolescents, and adults, dome osteotomies with/without additional operative procedures, such as ulnar nerve revision/transposition or ligament stabilizing, if necessary (**Fig. 6**). In the last 7 years, all multiplanar deformities of the distal humerus treated by the senior author (KM) were preoperatively planned using computed tomography (CT)-based three-dimensional (3D) planning and 3D prototyping [4, 9, 16, 19]. Although these planning procedures have become more and more expensive in recent years (as medical companies in this sector have started to reimburse their development costs), the authors are aware that multidimensional deformities in the modern era should not be planned two-dimensionally and, as such, challenge the medical insurance companies to cover the costs in all cases (which are on average €3500 per planning/rapid prototyping of templates) [1, 16].

As all four senior surgeons mainly work with adolescents and adults, one patient group they often see are patients with advanced posttraumatic cubitus valgus and tardy ulnar nerve palsy in adults. In line with Kang et al. and his group from South Korea, the authors perform corrective dome osteotomy with nerve transposition and double plating in such cases (**Fig. 7**; [17]). In adult patients with intraarticular malunion, the patient is consulted on the possibility of performing (preferably) 3D-guided intraarticular osteotomy, taking into consideration that these procedures are burdened with a high complication rate; the Amsterdam group around Patrick Kloen had three severe complications in their case series of six cases [16, 18].

Abstract · Zusammenfassung

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Corrective osteotomies at the distal humerus and forearm: a practical review

Abstract

Complex deformities of the distal humerus and forearm of either posttraumatic or hereditary origin have a significant negative impact on the functional integrity of the affected limb. They lead to pain, instability in both the elbow and the proximal/distal radioulnar joint, and profound motion deficit. Corrective procedures and more advanced surgical interventions for the main index procedures at the proximal forearm are extremely challenging for the treating upper extremity specialist due to the complex pathoanatomy in this region. This practical review focuses on the main aspects of correcting deformities of the distal humerus (malunion and non-union), the proximal forearm (differential therapy of chronic radial dislocation in children and adolescents), and the restoration of forearm rotation using rapid prototyping templates and computerized planning as the evolving standard technique in this region. In addition to the technical aspects, focus is put on planning (conventional vs. modern computerized three-dimensional (3D) planning), on different osteotomy techniques, and the surgical armamentarium that the specialist center should have available. Finally, some light is shed on the long-term outcome that can be expected and possible complications that can occur when performing these complex corrective procedures.

Keywords

Varus/valgus malunion of the distal humerus · Humeral condylar non-union · Rapid prototyping · Missed Monteggia pathology · Patient-specific implants (PSI)

Korrekturosteotomie des distalen Humerus und Unterarms – eine praktische Übersicht

Zusammenfassung

Komplexe Deformitäten im Bereich des distalen Humerus und des Unterarms, ob posttraumatisch oder hereditär bedingt, haben einen signifikant negativen Effekt auf die funktionelle Integrität der betroffenen oberen Extremität. Sie können Schmerzen, Instabilität im Ellenbogen und proximalen/distalen Radioulnargelenk sowie eine bedeutende Bewegungseinschränkung verursachen. Korrektureingriffe und anspruchsvollere chirurgische Eingriffe in diesen Indikationsbereichen sind gerade im Bereich des proximalen Unterarms aufgrund seiner komplexen Pathoanatomie eine echte Herausforderung für den behandelnden Spezialisten. Der Schwerpunkt dieser praktischen Übersicht liegt auf den wichtigsten Aspekten der Korrekturosteotomien des distalen Humerus („malunion" und „non-union") und proximalen Unterarms (Differenzialtherapie der chronischen Radiuskopfluxation bei Kindern und Adoleszenten) sowie auf der Wiederherstellung der Unterarmdrehung bei fehlgeheilten Unterarmfrakturen mit modernen 3-dimensionalen Schablonen („rapid prototyping") und computergestützter Planung als neues Standardverfahren. Neben den technischen Aspekten wollen wir uns insbesondere der Planung (konventionell vs. moderne computergestützte 3-dimensionale Planung), den möglichen Osteotomietechniken und dem im Zentrum vorzuhaltenden Instrumentarium widmen. Abschließend wird ein Ausblick auf die zu erwartenden Langzeitergebnisse und möglichen Komplikationen dieser aufwendigen Korrekturoperationen gegeben.

Schlüsselwörter

Varus-/Valgus-Malunion des distalen Humerus · Pseudarthrose der Humeruskondylen · „Rapid prototyping" · Übersehene Monteggia-Läsion · Patientenspezifische Implantate (PSI)

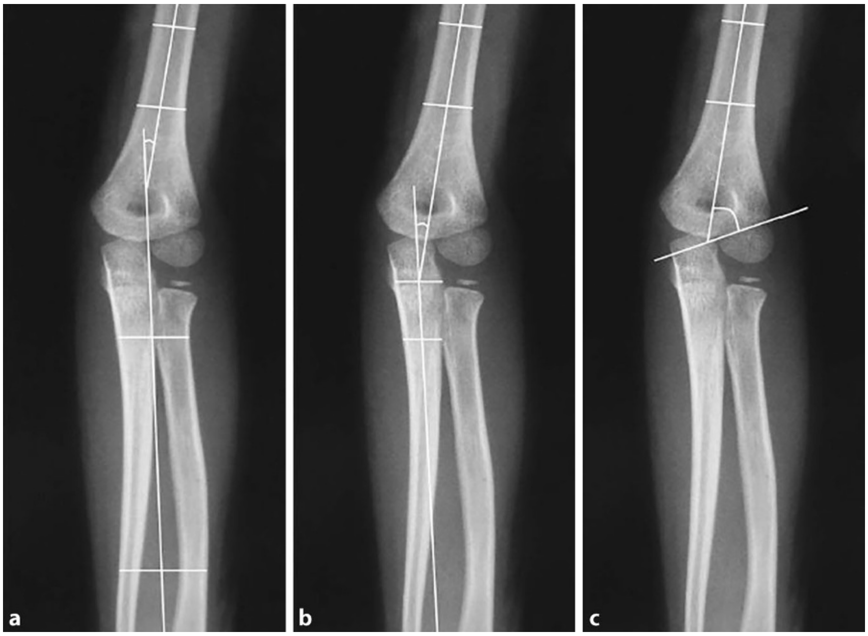

Fig. 3 ▲ The elbow axis is documented both clinically and radiologically by measuring the humerus-elbow-wrist angle, the Baumann angle, and the carrying angle. Modified after Inabaa et al. [15]

Principles of forearm corrections

Due to limited space in this review, focus is put on the missed Monteggia, as well as the authors' philosophy and treatment options for this difficult entity.

Correcting chronic radial head dislocation (missed Monteggia pathology)

Chronic radial head dislocation is mainly of posttraumatic origin and caused by overlooking a Monteggia fracture dislocation in childhood (therefore termed "missed Monteggia" or "chronic Monteggia lesion"). A second etiology in the authors' international consultancy between The Netherlands and Germany is a progressive forearm deformity with resulting chronic radial head dislocation in the case of the Masada IIB subtype of the rare hereditary disease multiple osteochondromata [3]. Hereditary radial head dislocation(often bilateral) and cases of overlooked chronic pediatric "pulled-elbow" are extremely rare. In children and adolescents with chronic Monteggia pathology, one most often sees the Bado subtype 1 (fracture of the diaphyseal ulna and anterior chronic dislocation of the radial head) and, more rarely, type IV (diaphyseal fracture of both forearm bones, anterior dislocation of the radial head) [10, 11, 21, 22]. While young children often display only mild symptoms and a moderate flexion deficit (caused by the abutment of the anterior radial head), progressive cubitus valgus with/without ulnar neural neuropathy later predominates clinically [21, 22]. In the late phase, hypertrophy and deformity of the radial head (so called mushroom-type deformity) leads to arthrosis and pain in the affected joint, coupled with dysmorphia of the proximal radioulnar joint and hypertrophy of the capitulum humeri.

In the early phase (unrelated to the patient's age and without manifest deformity or arthrosis), the authors advise a variety of corrective procedures, all aiming for *restitutio at integrum*: percutaneous osteotomy and correction of the ulna using a Minifixator (Orthofix®) [13] with/without open reduction of the radial head in the young child (<11 years of age); correction of the ulna with external fixator/plate with/without open reduction of the radial head (◘ **Fig. 8**; [21]); correction of both forearm bones using rapid prototyping techniques [1]; or complex correction of deformity using computerized ring fixators (Tl-HEX Orthofix® [Orthofix International, Verona, Italy], TSF Smith & Nephew® [Smith & Nephew, London, UK]) [1]. When a plate is used to correct the ulna and open reduction of the radial head is required, the authors use an extended radial approach (according to Pennig), using two windows (one dorsal to the anconeus muscle for corrective osteotomy of the ulna) and a modified Kocher approach for open reduction of the radial head ventral to the anconeus muscle (◘ **Fig. 8**).

In the late phase (with pronounced arthrosis and a dysmorphous proximal radioulnar joint), the authors advise two distinct salvage procedures, one being the so-called "functional radial head resection" according to Slongo, and a combination of radial head resection and interposition of the local anterior enlarged capsule according to Mader [12, 22]. All these corrective procedures in chronic radial head dislocations are challenging and should be performed in specialized centers. As the radial head resection interposition technique is described in detail elsewhere [12], "functional radial head resection" according to Slongo using a Taylor spatial frame (TSF; Smith & Nephew®) is described in detail here.

The principal operative procedure was described in 2008 by Teddy Slongo from Bern, Switzerland, as a salvage procedure in cases of chronic radial dislocation with arthrosis and restricted elbow flexion [22]. The technique was further developed by Fernandez and Mader in its modified form as "functional radial head resection" with a computerized ring fixator using the Taylor spatial frame [8]. To date, there are essentially two fixator systems available with the required versatility and software (TSF by Smith & Nephew© and TL-HEX by Orthofix©); both systems are used by the senior authors (KM, JH, DS and JH). Key points during the procedure include correct pin placement and osteotomy of the proximal ulna and the intraoperative calibration of the system, followed by postoperative calculation/control of the ulna and consecutive lengthening of the ulna with the transfixed radius, in order to transport the radius distally (◘ **Fig. 9**).

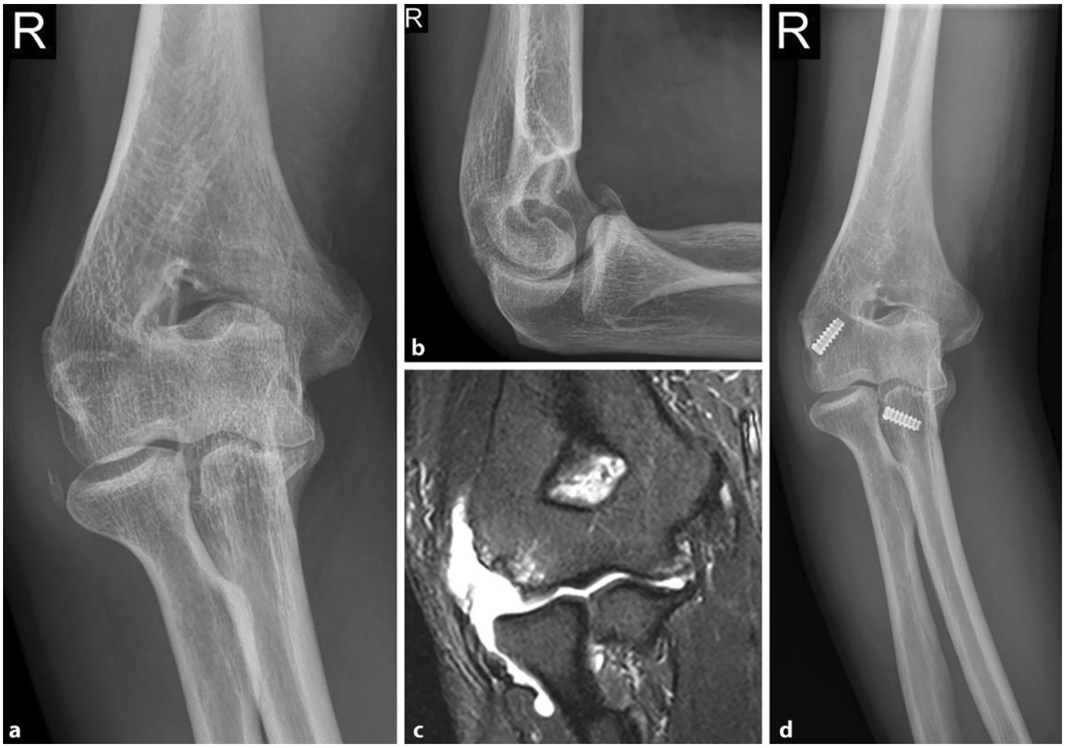

Fig. 4 ◀ X-rays and anteroposterior view (magnetic resonance imaging) of the right elbow in a 48-year-old male patient that sustained a fracture of the elbow as a child. Over the preceding 15 years, he had experienced multiple dislocations/subluxation episodes, pain, and instability of the radial side. Note the varus axis, the early arthritic changes, and the reactive changes of the medial humeroulnar joint. Revision of the lateral ulnar collateral ligament complex with triceps neoligament was performed, but failed after 6 months due to the altered biomechanical axis

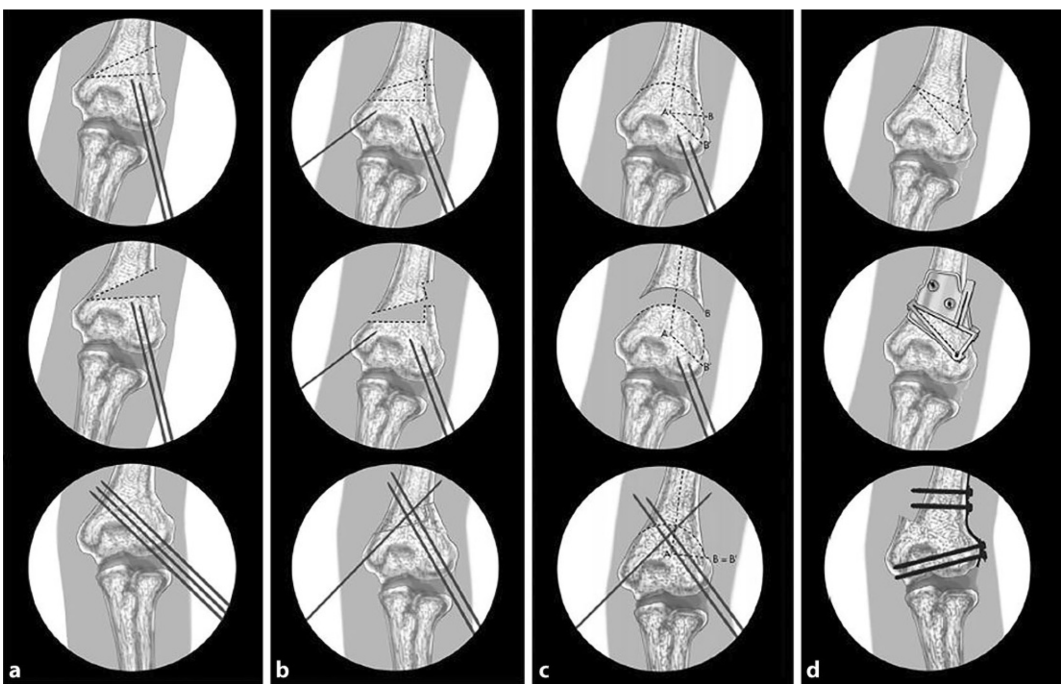

Fig. 5 ▲ Osteotomy techniques for varus deformity. **a** Lateral closing-wedge osteotomy: the main complication using this technique is the lateral condylar prominence. K-wires are placed for immediate fixation of the osteotomies. **b** Step-cut-osteotomy: the *dotted lines* mark the planned osteotomies. These osteotomies are more complex to plan and perform. **c** Dome osteotomy: the radius of the dome osteotomy (*AB*'as is the radius); again, predrilled k-wires are used for ease of fixation after correction of the deformity. **d** Three-dimensional osteotomy: *dotted lines* represent the planned osteotomies, which are made using preformed patient-specific cutting guides. (Modified from [6]. With courtesy of Elsevier)

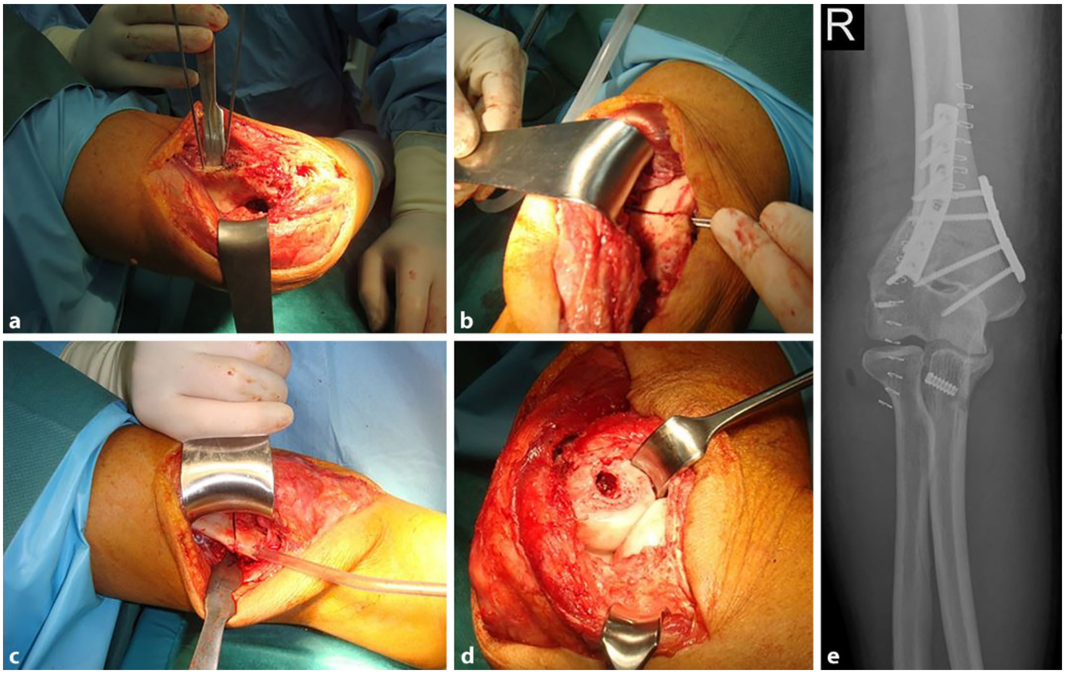

Fig. 6 ◂ Intraoperative images and postoperative anteroposterior X-ray of the patient from **Fig. 4**. After preoperative counseling, a closed-wedge valgus osteotomy was performed, stabilized with double plates, and redo lateral ulnar collateral ligament reconstruction (using gracilis) performed, and an additional hinged fixator used

Hydroxy-apatatite (HA)-coated fixator pins are used, hence the mean fixator time is 3–4 months. Using a bloodless field after single-shot antibiosis, the anatomical landmarks are marked under fluoroscopic guidance, i.e., the level of the osteotomy and the position of the four ulnar and the one radial pin (**Fig. 9**). The first pin is at a right angle to the main axis of the ulna (all HA pins are conical, 3.5–4.5 mm, and predrilled). The premounted double-ring system (one ventrally open half-ring proximally and a slightly smaller full ring fully mounted with struts distally) is fixed to the pin, followed by the distal ulnar pins and the second proximal ulnar pin to add stability to the construct. In neutral forearm rotation, a pin is inserted into the distal third of the radius (open in order to avoid damage to the superficial branch of the radial nerve). Using a calibration ball or calibration screw, the position of the rings to the bones and the deformity are recorded for later use in the computer software setup. All screws are fixed on the frame and, using a limited dorsal approach to the proximal ulna, a total drill and chisel osteotomy is performed at the preplanned position (**Fig. 9**). Using the "mounting parameter," the software is calibrated and, after a waiting period of 7–10 days, first the correction of the ulna (20–30°) and then the lengthening (or callotasis) of the ulna with fixed radius is performed. Both systems offer App-controlled correction with feedback to both the patient and treating surgeon. A special follow-up unit is mandatory for these procedures: special equipment is needed to change struts and/or monitor the progress of the correction. Depending on the lengthening, and once the desired correction has been achieved, after the consolidation of the re bony regnerate the frame is removed and physiotherapy follows. The frame is removed after healing (**Fig. 8h, i**).

Armamentarium and results

This group of international authors oversee comparatively large consecutive case cohorts of corrective procedures of the distal humerus and the forearm in the collaborating referral centers in Amsterdam and Hamburg (in which nearly all complex corrective procedures are performed with two attending consultants together). Over a time span of 18 years, they have overseen more than 155 corrections at the elbow and forearm with both posttraumatic and hereditary etiology. In addition to the outpatient and counseling facilities, an extensive armamentarium of both operative equipment and technical tools is available, ranging from k-wires (simple and cheap), modern plating systems integrated into computerized planning tools, monolateral/ring fixators to rapid prototyping techniques (**Fig. 10**), and a variety of computerized planning options. Both centers are working closely with medical engineers and industry and have established a well-functioning follow-up/postoperative monitoring unit in order to minimize intraoperative surgery-related and postoperative fixator-related complications.

At the distal humerus, consistent with the authors' and other current case series and in line with the recent meta-analysis by Sofelt et al., one can expect (and use in the informed consent) good and excellent results in 88% of cases and an overall risk for complications (using whichever technique the surgeon is familiar with and is suitable for the individual patient) is 15%. The latter include nerve injury (around 2.5%), residual deformity (around 6%), infection (2.5%, rising up to 7% if external fixation is used), and possible reoperation for a variety of reasons. The use of the novel modern (and expensive) computer-based planning and osteotomy techniques described here improve pre- and intraoperative planning as well as surgical execution; however, they require

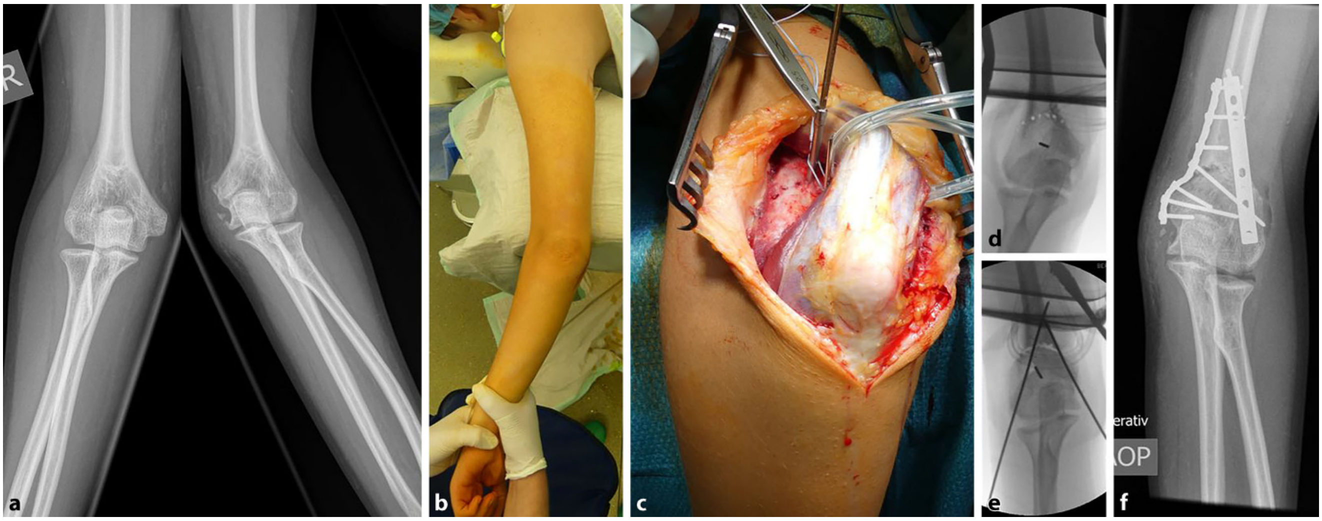

Fig. 7 ▲ **a** Preoperative xray of the elbow in a 16 year-old female patient with posttraumatic cubitus valgus left. **b** Intraoperative image showing positioning of the patient in prone position with a short arm table. **c** Dorsal approach to the distal humerus (triceps on) after drill-dome-osteotomy. **d, e** Intraoperative fluoroskopic images of the same patient showing the dome osteotomie and the correction of the valgus with temporary k-wires in situ. postoperativ ap xray a er correction with plates in situ

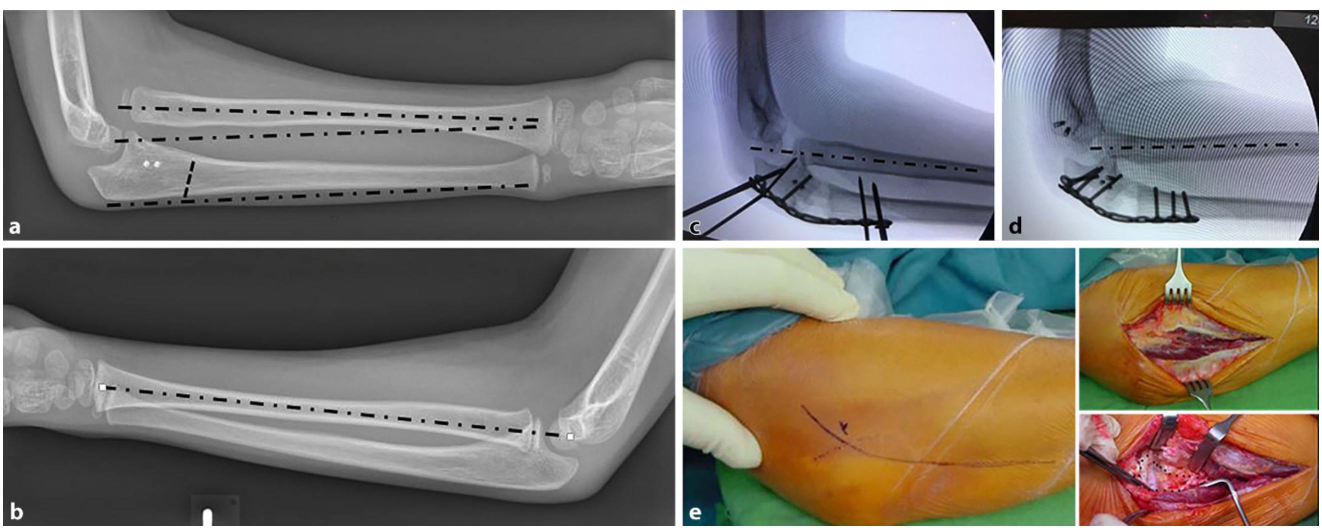

Fig. 8 ▲ **a, b** Preoperative bilateral long forearm X-rays in an 11 year-old girl with missed Monteggia pathology: note the positive Støren line and the ulnar bow sign. A frustrated attempt at open reduction of the radial head (so-called Bell-Tawse operation) was performed using bone anchors. **c, d** The corrective osteotomy was performed using a proximal ulna subtotal osteotomy and a plate using an extended lateral approach according to Pennig; this allows for the corrective osteotomy and the open insertion of the radial head in the proximal radioulnar joint through one approach (case provided by Konrad Mader, Hamburg)

a more aggressive surgical approach and undoubtedly interfere more with soft tissue and neurovascular structures in the area; in complex forearm corrections using rapid prototyping technology, the authors experienced some bleeding complications and two cases of compartment syndrome due to extensive exposure and long operating times [1, 16, 19, 23].

In complex forearm corrections, and here in chronic Monteggia pathology patients, an individualized treatment plan depending on the deformity, the age of the patient, and the status of the radial head and the PRU joint can either lead to a near anatomic reconstruction with good functional result or, in cases of longstanding deformity and established arthrosis, salvage procedures with good pain reduction and functional improvement. Here the complication rate (in the authors' consecutive series) is >10%, comprising nerve injury (under 2%), residual deformity (around 6%), pin-site related infection (3%), reoperation for postoperative ulnar plus deformity, hardware removal, and soft tissue revision [1, 3, 12, 13, 21]. All complex corrections, e.g., fixator-based techniques, are prone

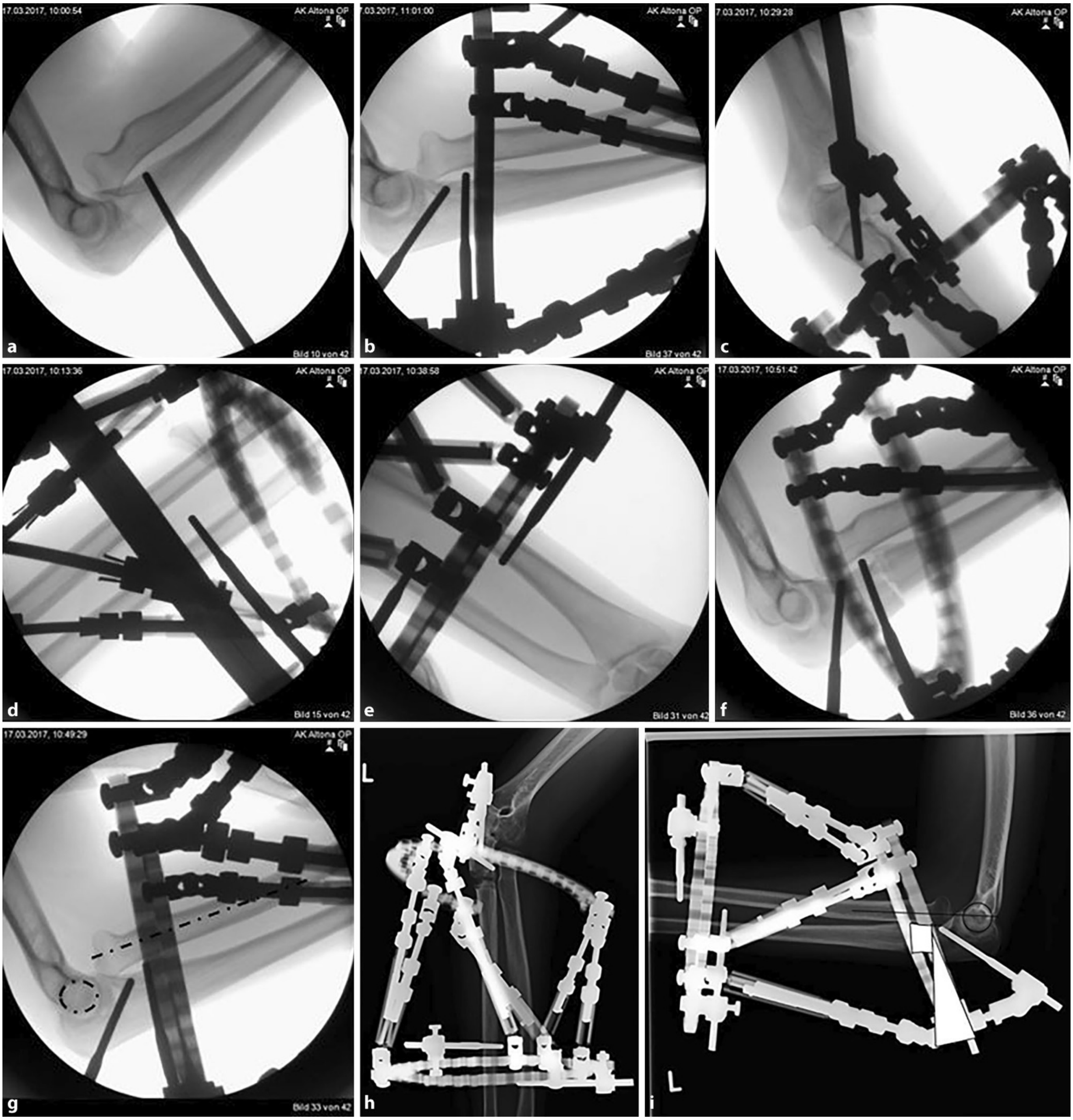

Fig. 9 ▲ **a–g** Intraoperative fluoroscopy images showing the key intraoperative steps in the "functional radial head resection according to Slongo" procedure. **h, i** Postoperative X-rays 4 months after the index operation (**Fig. 8**): the osteotomy and lengthening are consolidated and the frame is removed as an outpatient operative procedure (HA-coated pins are painful to remove). Note the lengthening of the ulna, the correction of the deformity, and the positioning of the radial head

to severe complications in inexperienced hands and are centralized in specialized centers.

Practical conclusion

Complex deformities of the distal humerus and forearm have a significant negative impact on the functional integrity of the affected limb and cause pain, joint instability, and profound motion deficit.

Corrective procedures and more advanced surgical interventions for the main index procedures at the proximal forearm are extremely challenging for the treating upper-extremity specialist due to the complex pathoanatomy in this region. In cases of complex defor-

Fig. 10 ▲ Custom-made rapid prototyping of the distal humerus and full forearm of a 21-year-old patient with a neglected Monteggia deformity. The printout is part of the "extended work-bench" project at the University Medical Center Hamburg-Eppendorf, Germany, where these printouts are used to pre-operatively plan complex ring fixator corrections before the actual surgical procedure

mities in more than one plane at the distal humerus, as well as in cases with rotational deformity in the forearm, 3D planning with/without patient-specific templates is increasingly used, since rotational deformities cannot consistently and accurately be calculated by traditional planning techniques. Missed Monteggia is mainly of posttraumatic origin and caused by overlooking a Monteggia fracture dislocation in childhood. Chronic missed Monteggia deformity inevitably results in loss of flexion, forearm rotation, and arthritic deformity of the radiocapitellar joint. At the distal humerus, one can expect good and excellent results in 88% of cases and an overall risk for complications (using whichever technique the surgeon is familiar with and is suitable for the individual patient) of 15%. All complex corrections are prone to severe complications in inexperienced hands and are centralized in specialized centers.

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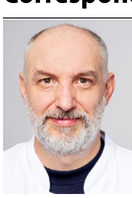

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Compliance with ethical guidelines

Conflict of interest K. Mader, M. Farkhondelfal, J. Ham, M. Flipsen, J. Nüchtern, S. Schlickewei-Yarar, K. Wintges, D. Seybold and B. Hollinger declare that they have no competing interests.

For this article no studies with human participants or animals were performed by any of the authors. All studies performed were in accordance with the ethical standards indicated in each case.

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