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Three-dimensional computer-assisted corrective osteotomy with a patient-specific surgical guide for an antebrachial limb deformity in two dogs

Longo, Francesco; Penelas, Alexandra; Gutbrod, Andreas; Pozzi, Antonio

Abstract: We describe patient-specific surgical guide prototyping and surgical treatment of a complex antebrachial deformity in two skeletally mature dogs presenting with chronic lameness. Computer-assisted surgery was elected to increase accuracy in the correction of the complexity deformity. Radiographs and CT scans revealed a biplane deformity with valgus, procurvatum and external torsion of the right radius in both cases. The pre-surgical planning started from the quantification of the angular deformity, computer simulated correction to end up with a rehearsal surgery on 3D printed bone models. During the surgery, the custom-made osteotomy guides closely fitted the bone, allowing for a precise corrective osteotomy, that was stabilized with two locking plates. Postoperative x-rays showed successful correction of the deformity. At the follow up recheck examinations at 8 and 12 weeks postoperatively the dogs had improved lameness, weight-bearing and progression of bone healing were observed in both dogs. Patient-specific surgical guides allowed for a satisfactory correction of the antebrachial deformity. Additional benefits of using customized surgical devices include standardization and reduced surgical time.

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1 **THREE-DIMENSIONAL COMPUTER-ASSISTED CORRECTIVE**
2 **OSTEOTOMY WITH A PATIENT-SPECIFIC SURGICAL GUIDE**
3 **FOR AN ANTEBRACHIAL LIMB DEFORMITY IN TWO DOGS**

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Summary

We describe patient-specific surgical guide prototyping and surgical treatment of a complex antebrachial deformity in two skeletally mature dogs presenting with chronic lameness. Computer-assisted surgery was elected to increase accuracy in the correction of the complexity deformity. Radiographs and CT scans revealed a biplane deformity with valgus, procurvatum and external torsion of the right radius in both cases. The pre-surgical planning started from the quantification of the angular deformity, computer simulated correction to end up with a rehearsal surgery on 3D printed bone models. During the surgery, the custom-made osteotomy guides closely fitted the bone, allowing for a precise corrective osteotomy, that was stabilized with two locking plates. Postoperative x-rays showed successful correction of the deformity. At the follow up recheck examinations at 8 and 12 weeks postoperatively the dogs had improved lameness, weight-bearing and progression of bone healing were observed in both dogs. Patient-specific surgical guides allowed for a satisfactory correction of the antebrachial deformity. Additional benefits of using customized surgical devices include standardization and reduced surgical time.

Key words

Bone deformity, computer-assisted surgery, dogs, patient specific surgical guides, rehearsal surgery

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53 Zusammenfassung

54 Der Bericht beschreibt den Prototyp eines patientenspezifischen chirurgischen Guides mit dessen
55 Hilfe bei zwei ausgewachsenen Hunden mit chronischer Lahmheit die chirurgische Versorgung
56 einer komplexen Unterarmdeformität durchgeführt werden konnte. Aufgrund der Komplexität der
57 Knochendeformation und der geplanten Operation wurde eine computerassistierte Chirurgie
58 gewählt. Sowohl die Röntgenbilder als auch die CT-Studien zeigten biplanare Deformitäten mit
59 Valgus, Prokurvatum und Aussenrotation des rechten Radius auf. Die präoperative Planung
60 beinhaltet die Quantifizierung der Deformität, die Computersimulation der Korrekturosteotomie
61 und die Durchführung der Operation an 3D gedruckten Knochenmodellen. Die spezialangefertigten
62 Osteotomie-Guides wiesen intraoperativ eine akkurate Knochenanpassung auf, welche präzise
63 Korrekturosteotomien erlaubten. Die Osteotomien wurden mit zwei Verriegelungsplatten
64 stabilisiert. Die postoperativen Röntgenbilder zeigten in beiden Fällen eine gelungene Korrektur der
65 vorangegangenen Deformitäten. Die klinischen und röntgenologischen Kontrollen nach 8 und 12
66 Wochen wiesen eine abnehmende Lahmheit, zunehmende Gewichtsbelastung und progressive
67 Knochenheilung bei beiden Hunden nach. Die Patientenspezifischen chirurgischen Guides
68 erlaubten akkurate Osteotomien und Korrekturen der Unterarmdeformitäten. Ein zusätzlicher
69 Nutzen solcher spezifisch angepassten chirurgischen Vorrichtungen ist eine mögliche
70 Standardisierung und eine Verkürzung der Operationszeit.

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72 **Schlüsselwörter**

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74 Knochendeformation, Computerassistierte Chirurgie, Hund, patientenspezifische chirurgische
75 Guides, Testoperation

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Introduction

Bone deformities of the antebrachium represent the most frequent form of angular deformity in dogs⁷ and often need corrective osteotomy to be treated appropriately^{6,15}. To achieve this goal, an accurate study of the bone alterations based on center of rotation of angulation (CORA) methodology is imperative¹⁵. Preoperative planning for antebrachial deformity has been described based on orthogonal radiographs^{3,6}. However, advancements within the orthopedic field have introduced three-dimensional (3D) imaging techniques such as computed tomography (CT)¹⁴ and computer-aided-design (CAD) software^{8,16} to enhance visualization of bone models. The acceptance of computed-based technology has strongly encouraged the customization and surgical use of 3D printed guides to aid surgeons intraoperatively¹.

The present case report describes the design, prototyping and surgical application of 3D custom-made guides, which were used as computer-assisted devices to treat a biplane bone deformity of the antebrachium in two dogs.

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Case report

Two castrated male dogs were referred to the Small Animal Hospital of the University of Zurich for a chronic lameness on the right front limb.

Case 1 was a 7 years-old, mixed-breed dog, weighing 19.1 kg. On visual examination, the dog exhibited a 2/4° front right lameness. Radial procurvatum, valgus as well as external torsion of the distal right front limb were visible. At physical palpation, moderate atrophy of the antebrachial muscles, mild reduction of the range of motion (ROM) of the right elbow and painful carpal flexion were found. An orthogonal radiographic study (Fig. 1a), followed by a CT examination of the front limbs, showed mild incongruence of the right elbow joint, shortening of the ulna, proximal displacement of the radial styloid process, valgus and torsional deformities in the right antebrachium.

Case 2 was 3 years-old Shih Tzu of 3 kg. On visual examination, a 2/4° front right lameness was noted along with the presence of radial procurvatum, valgus and external torsion of the paw. The physical examination revealed mild atrophy of antebrachial musculature with diminished and painful ROM of the elbow. Radiographic and tomographic findings (Fig. 1d) confirmed the clinical findings, showing an elbow incongruence with severe shortening of the ulna, presence of a large intra-articular fragment compatible with a fragmentation of medial coronoid process, radial head subluxation and flattening of the ulnar trochlear notch.

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Computer Assisted Preoperative Planning

The preoperative planning was carried out with the assistance of an engineering company (IRPD, St. Gallen, Switzerland) and consisted of four steps:

- 1- The anatomical proximal and distal radial angles were measured on craniocaudal and mediolateral radiographs of the affected radius. On the craniocaudal view, the anatomic medial proximal radius angle (aMPRA) measured 69° (case 1) and 53° (case 2), while the lateral distal radius angle (aLDRA) was 78° and 76° respectively. On mediolateral view, the anatomic proximal caudal radius angle (aCdPRA) measured 99° (case 1) and 122° (case 2); while the distal caudal radius angles (aCdDRA) was 58° and 75° respectively. The magnitude of CORA was for case 1: 28° valgus and 34° procurvatum and for case 2: 15° valgus and 31° procurvatum.
- 2- The right antebrachium was segmented with a commercially available DICOM software (Osirix, Pixmeo, Switzerland) and a stereolithographic (STL) file was created to obtain a 3D surface bone model. The STL file was imported in a CAD software where it was elaborated. A computer-simulated correction was performed. A closing wedge was removed from the medial and cranial radial cortices, based on either the quantification of the deformity or the CORA location. The bones were then digitally aligned in a new position, reaching parallelism between proximal and distal joint reference lines (Fig. 2a,b). The new antebrachial positioning was compared to the starting bone alignment (mirror image function).
- 3- The osteotomy guide was set up on the basis of the quantification of the closing wedge and on the profile of the dorsal radius. This custom-made surgical device was designed to have two

164 osteotomy slits functioning as plane guides: the angle of intersection of the two osteotomy slits was
165 equivalent to the magnitude of the CORA. The printed guide included two holes with a co-planar
166 orientation on both sides to temporary fix the guide on bone through K-wires (Fig. 3a,b).

167 4- The osteotomy guide was prototyped and manufactured in a true to real scale with a material that
168 could be sterilized and shaped in surgery (Polyamid 12). Several bone models (Polylactic acid) of
169 the affected antebrachia were 3D printed (Drukarka 3D, 3D Gence SP., Poland) to perform a
170 rehearsal surgery. During the rehearsal corrective osteotomy, the fitting and shaping of the
171 osteotomy guide on the radial cortex as well as the feasibility of deformity correction were checked.
172 Locking plates (ALPS, Kyon, Zurich) were contoured to fix the bone fragments and then sterilized
173 for the surgery.

174 Surgery 175 176

177 A cranial approach to the radius was performed, extending the skin incision from the radial
178 diaphysis to the carpal joint. The custom-made osteotomy guide was positioned on the radius and
179 temporarily fixed with four 1mm K-wires (Fig 4a). A closing wedge osteotomy of the radius was
180 executed with an oscillating saw by aligning the saw blade with the osteotomy slits (Fig. 4b). A
181 lateral approach to the ulna was made through a skin incision from the ulnar styloid to the midshaft.
182 An ulnar ostectomy was performed. The osteotomy guide was removed, and external torsion was
183 corrected intraoperatively aligning the carpus to the elbow. The correction of the valgus and
184 procurvatum deformities was achieved by aligning the radial fragments with bone reduction forceps
185 (Fig. 4c). The pre-contoured locking plates (ALPS 8 and 6.5) were fixed on the craniolateral and
186 medial cortex of the radius using locking and cortical screws (Fig. 4d). To promote bone healing,
187 autogenous cancellous bone graft was collected from the proximal humerus and packed around the
188 radius osteotomy and ulnar gap. The surgical wound was closed routinely.

189 Orthogonal postoperative radiographs showed a correct implant positioning and an improved
190 antebrachial alignment (Fig. 1b, e). Cage rest was recommended for 6-8 weeks. Activity was
191 restricted to ten minutes walking with 2-3 times per day and gradually increased until complete
192 bone healing. Radiographs rechecks were planned at 4, 8, and 12 weeks.

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197 Follow-up examination

198 Case 1 significantly improved at the 4-week recheck examination. A minimal lameness ($1/4^\circ$) along
199 with mild painful carpal palpation and reduced carpal ROM in flexion were noticed. Recheck
200 radiographs showed loosening of the proximal locking screw of the cranial-medial plate, and thus
201 the screw was removed. At the 8-weeks recheck the weight bearing of the operated limb improved
202 and the radiographs showed a progressive new bone formation at the osteotomy sites (Fig.1 c). The
203 osteotomy was completely healed at the 12 week-recheck. A second proximal locking screw of the
204 craniomedial plate was loose and therefore removed. At 1-year recheck examination the dog
205 showed no lameness with an improved and pain free carpal ROM.

206 Case 2 improved at the 4-week recheck examination, but still presented a $2/4^\circ$ right front limb
207 lameness and moderate painful elbow palpation. Radiographs showed an advanced healing of the
208 radial osteotomy as well as a decreased radio-ulnar step with moderate osteophytosis in the cranial
209 aspect of the radial head. At 8 and 12-weeks rechecks new bone formation was found with an
210 increased radiopacity in the radius and solid new callus formation in the ulna gap. A mild
211 radiolucency surrounding one distal and two proximal screws was noticed, therefore these screws
212 were removed (Fig.1 f). At the final 16-weeks recheck the dog exhibited a $1/4^\circ$ right front limb
213 lameness. At palpation an increased antebrachial muscular tone and a mild painful ROM of the
214 right elbow were found.

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Discussion

We found that the computer-assisted corrective osteotomy allowed a correction of the deformity with a simple intraoperative execution of the preoperative planning. The application of the osteotomy guides to the distal radius was facilitated by the profile adjusted to the true-sized bone model derived from CT images. As a result, no time was spent in manually finding the planned osteotomy site. We found that the custom-made osteotomy guides closely fitted the bone without extensive soft tissue dissection. Furthermore, neither use of additional joint-oriented K-wires nor fluoroscopy were needed. Both patients had a positive clinical outcome with an improved limb use. Despite the strong fixation provided by the double plate technique, we had some minor implant-related complications, which were easily managed and did not compromise the success of the surgeries. We opted for using a double plate fixation, based on the complex biplane nature of the deformity. In addition, the use of two smaller plates rather than a single large implant may decrease the impingement between implant and extensor tendons. Advantages of computer-assisted surgical techniques involve both preoperative and intraoperative phases of corrective osteotomies. First, CAD software enables the user to manipulate the bone model, design bone wedges and detect the planes of the articular surfaces¹³. A mirror imaging function is available to superimpose the affected region on either the original alignment of the bone

242 or the contralateral reference limb, enabling a precise deformity correction. Second, rehearsal
243 surgeries could be performed on 3D printed bone models, allowing to test the guides before the
244 surgery ^{9, 12}. The rehearsal surgery was useful because we slightly modified the printed guides to
245 improve the fitting on the radius and adjust the angle of the osteotomies. Additionally, we were able
246 to pre-contour all the implants, without the need of intraoperative modifications and, thus,
247 decreasing the surgical time. Third, performing a free-hand osteotomy may potentially lead to
248 errors. The patient-specific osteotomy guides act as precise intraoperative localizers of the CORA
249 and provide a controlled guidance during the osteotomy. Therefore, we may speculate that these
250 devices could be helpful for surgeons who are at the initial learning curve for the treatment of such
251 complex bone deformities.

252 The potential drawbacks of computer assisted surgery are the cost and the time required to plan and
253 print the osteotomy guides. The time for performing the preoperative plan is mainly related to the
254 type of CAD software used and the learning curve for correctly elaborate the 3D data. The cost is
255 mostly associated with the stereolithography modelling and guide prototyping. When considering
256 the cost-benefit of computer assisted surgery, animal with complex deformities may be the best
257 candidates for these advanced techniques.

258 The correction of biplane antebrachial deformities requires a detailed planning to localize and
259 quantify the malalignment and to limit the complication rate ^{2,7}. It may be not feasible to accurately
260 evaluate such complex bone deformities neither with a 2D radiographic study nor CT ^{4,10}.

261 Furthermore, as extensively demonstrated in human medicine (REF computer assisted vs free-
262 hand), computer assisted-surgeries could be more accurate and faster than free-hand techniques
263 when performing osteotomy ¹³ fracture fixation ¹⁷, joint replacement surgery ¹¹ and vertebral screw
264 placement as well ⁵.

265 With regard to torsional correction, several papers reported the use of reduction guides, which
266 allow for achieving a precise reduction of bone fragments ^{9,10}. These devices are designed to have

267 the proximal K-wire holes not aligned with the distal holes. As a result, a correction of a torsional
268 deformity is achieved by aligning the K-wires after the completion of the osteotomy.

269 In this study, we didn't diagnose a severe external torsion of the distal antebrachium and thus we
270 opted for a visual alignment of the carpus to the elbow, before the final bone reduction. The use of
271 joint-oriented K-wire could have been an efficient strategy for performing a more controlled
272 correction of the torsional deformity. Alternatively, an external circular or hybrid fixator could have
273 represented a useful surgical option for either osteotomy reduction or fixation of bone fragments.

274 In conclusion, we reported the prototyping and surgical application of patient-specific osteotomy
275 guides, which allowed for a deformity correction that led to a successful clinical outcome. The
276 reestablishment of a more physiological alignment of the antebrachium and carpus loading might
277 limit the development of osteoarthritis in the medium-long term, thus decreasing chronic pain.

278 Rehearsal surgeries and custom-made osteotomy guides represent favorable solutions for surgeons,
279 who are challenged by the treatment of complex corrective osteotomies. In our experience, the
280 surgically assisted correction of the angular limb deformity was straightforward compared to
281 standard osteotomy and reduction technique.

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Figure legends

Fig. 1: Orthogonal radiographic studies of case 1 (upper line) and case 2 (lower line). Craniocaudal and mediolateral radiographic projections showing a biplane antebrachial bone deformity (a and d). On the craniocaudal projection, the presence of a valgus deformity was observed. A severe lateral subluxation of the radius head was also noticed in case 2 (d). A cranial bowing of the radius and a distal antebrachial torsion were detected on the mediolateral projection. Images (b and e) depict immediate postoperative radiographs. The craniocaudal and mediolateral projections show the correction of the radius valgus and procurvatum as well as the presence of an ulnar osteotomy. A double plating technique with hybrid locking implants was used. Images (c) and (f) show the 12-weeks radiographic recheck. A complete bone healing at the level of radius osteotomy was detected. On image (c) a loosening of the proximal locking screw of the smaller plate (c) was found.

393 Another proximal locking screw of the same implant was previously removed at 8-weeks recheck.

394 Image (f) shows that 3 screws were removed from the craniolateral plate following the detection of
395 an increased radiolucency close to screws.

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397 Fig. 2: Computer assisted preoperative planning. A closing bone wedge was created in the bone
398 model to correct frontal and sagittal deformities. The osteotomized bones were manipulated to reach
399 a new alignment (red and green bone models). The post-corrective antebrachial alignment was
400 compared to the pre-corrective alignment (blue and purple bone models) by means of mirror image
401 function. Red arrows indicate (a) the translation of the distal antebrachium on the sagittal plane.

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403 Fig. 3: Three-dimensional printed patient-specific osteotomy guides. Image (a) shows the temporary
404 fixation of the osteotomy guide. Image (b) shows the design and simulated application of the
405 osteotomy guide onto the radial surface. The distal medial edge of the osteotomy guide was planned
406 to anatomically match the profile of the medial ridge of the radius groove.

407 Fig. 4: Intraoperative images of case 1. Temporary fixation of the osteotomy guide with four K-
408 wires (a). Execution of the radius closing wedge osteotomy (b): the osteotomy guide slits support
409 the drill blade and guide the osteotomy. Anatomical bone reduction: a new antebrachial alignment
410 was achieved (c). Radial double plate fixation using pre-contoured locking implants (d).

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