Computer-assisted surgical correction of an antebrachial deformity in a dog

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Keywords
Computer-assisted surgery, computer-aided surgery, rapid prototype modelling, angular limb deformity, three dimensional

Summary
Objective: To report the use of three dimensional (3D) computed tomographic (CT) imaging, computer simulation and rapid prototype modelling to aid surgical correction of a complex antebrachial deformity in a dog.
Methods: A six-year-old, 13 kg spayed female Chihuahua crossbreed dog was presented for worsening forelimb gait and exercise intolerance. Both forelimbs had gross angular limb deformity with carpal hyper-flexion, valgus and radial procurvatum. Surgical planning from radiographs was problematic therefore CT data were used to generate 3D reconstructions of the antebrachium. Using imaging software we then quantified the nature of the deformity using a previously unreported method based on the centre of rotation of angulation as a 3D model. Computer simulated closing of the virtual wedge osteotomy was then performed as proof of concept. A stereolithographic model complete with osteotomy axes, was then created in plastic using a rapid prototyping machine. Oscillating saw guides were fabricated in polymethylmethacrylate and cold sterilised. A closing wedge osteotomy with de-rotation was performed and stabilised with a pre-contoured dynamic compression plate. At the three- and six-month follow-up examinations there was improved weight-bearing and cosmetic appearance.
Conclusions: Computer assistance was valuable for locating and quantifying this antebrachial deformity and conceptualising the corrective surgery. The results of our study suggest that rapid prototyping can be used to create models and saw guides to simplify one-stage corrective osteotomies and more accurately treat angular limb deformity.

Case report
A six-year-old, 13 kg, spayed female Chihuahua crossbreed dog was evaluated for a forelimb gait abnormality and inability to exercise. Both forelimbs had rotational and angular deformities with marked radial bowing and excessive carpal flexion. The left forelimb was the worst affected, with an estimated 80° of external rotation of the carpus (Fig. 1). The owners reported that the dog had suffered a fall onto the extended forelimbs as a puppy. At the initial diagnosis of ALD conservative management had been advised, however debility had progressed to limited exercise tolerance and intermittent non-weight-bearing lameness of the left forelimb. When the dog walked, the carpus would hyperflex and buckle under, throwing the dog’s weight forward.

Introduction
Deformity of the antebrachium is the most common form of angular limb deformity (ALD) in dogs (1). Premature closure of the distal ulna physis due to trauma is the most common aetiology (2–6). Surgical correction is indicated when there is altered mobility and exercise intolerance due to deformity or to reduce progression of secondary osteoarthritis. Preoperative planning has traditionally involved measurements from orthogonal radiographs (2, 5, 7). Corrective surgery usually involves osteotomy with either an opening or closing wedge technique (3, 5, 6). Dome osteotomy has also been described (8). After correction, fixation can be achieved with either external skeletal fixation or internal plating osteosynthesis based on patient factors and surgeons preference (3, 5, 9, 10)

The major challenge in correcting angular limb deformities is accurately determining the nature and extent of the anatomical deformity. Radiographs provide only two dimensional data and the existing methods for surgical planning may be inaccurate in complex deformities. In this case we used advanced imaging, computer aided simulation, rapid prototype modelling and rehearsal surgery to improve the accuracy and confidence in our surgical treatment.

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with both areas accurately positioned in a cranio-caudal projection. The segmental radiographs are then juxtaposed to obtain a view of the entire limb. In this case segmental radiographs were not performed because the authors considered that this method still attempts to identify a three-dimensional (3-D) deformity in two axes. Therefore it was decided to perform computed tomographic (CT) imaging and create 3-D models to both eliminate the difficulty in accurate isolation of the anatomical landmarks and to aid in the identification of axes of the deformity.

A CT scan of both forelimbs was performed while the dog was under general anaesthesia using a six-slice helical scanner. The dog was positioned in sternal recumbency with both forelimbs extended cranially allowing the carpi, metacarpi and digits to lie in a neutral position. Transverse 1 mm slices were obtained beginning at the proximal humerus and extended to include the digits using a bone algorithm (W:1500 L:500). For the left forelimb three-dimensional (3D) reconstructions were created using the CT scanner workstation and the raw CT data were exported in DICOM format for further manipulation.

Using commercial software\textsuperscript{b}, the DICOM data were converted to an STL file (stereolithography CAD software file format) then manipulated with software\textsuperscript{c}. Three-dimensional computer models were generated which could be rotated and viewed from any angle. The carpal bones were removed from the model to improve visualisation of the articular surface of the distal radius. Accurate identification of the planes of the articular surfaces was performed by isolating anatomical landmarks and changes in gradient of the bone surface using a surface contour mode. For the elbow joint, the proximo-lateral radial head and proximo-medial coronoid process were used as markers in the cranio-caudal axis, and then by rotation of the 3D image, the medio-lateral and axial components of the joint surface were also identified. At the distal radius, a similar process of rotation of the 3D model and gradient assessment allowed isolation and connection of multiple points on the joint surface and therefore identification of the articular plane (Fig. 3). As there was no normal data for the 3D trajectory of the radius from its proximal and distal joint surfaces, and due to unfamiliarity with the capabilities of the system, it was decided to use a tangent at 90° to either plane. When these lines were extended proximally and distally they did not meet in space, as expected for a bi-apical deformity. To identify the point at which a single corrective osteotomy could be made, the two joint planes were advanced along these projected axes from both the elbow and carpus.

A point along the radius where the distal projected axis exited the radial cortex was identified and set as the apex of the wedge (Fig. 3). The CopyCAD Pro software enabled us to remove this wedge and manipu-

\textsuperscript{a} Phillips Brilliance, Philips Healthcare, Andover, MA, USA.

\textsuperscript{b} ScanIP: Simpleware Ltd, Exeter, UK

\textsuperscript{c} CopyCAD Pro Design: Delcam PLC, Birmingham, UK

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**Fig. 1** Preoperative appearance of a six-year-old, 13 kg Chihuahua crossbreed dog with marked valgus and procurvatum of the antebrachium. The carpus was externally rotated approximately 80° and the dog walked with carpal hyperflexion.

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late the proximal and distal fragments electronically to appose the radial cortices and correct the rotation of the distal segment, hence simulating the closing wedge ostectomy to be performed on the dog (Fig. 4). Closure of this single wedge defect allowed appreciation of the postoperative appearance of the radius and an assessment of the amount of limb shortening. The simulation indicated that with correction based on these axes, the radial limb would be entirely straight through the antebrachium, and that the rotation and lateral bowing would be corrected without significant loss of limb length.

Stereo-lithographic models of the distal humerus, radius and ulna were then produced in acrylnitrile butadiene styrene plastic using a fuse deposition modelling 3D printer. One model was kept intact as a reference, whilst another model was produced with the computer generated wedge osteotomy planes extending from the bone surfaces as flanges (Fig. 5). This model was then surface waxed and polymethylmethacrylate (PMMA) in dough phase was contoured to the radius and built up on either side of the flanges to a depth of 5 mm, creating saw guides (Fig. 5). Once hardened these guides were removed from the model and set aside to be used during surgery. The proposed surgery was rehearsed on the flanged model, with cuts made along the planes to generate an accurate representation of the wedge osteotomy. The authors felt that correction to an entirely straight radius as indicated on the computer model would be ‘over-correction’ for a chondrodystrophic dog. A decision was made to reduce the angle of the ostectomy wedge in the cranio-caudal plane. This was achieved by filing of the ends of the fragments and using additional PMMA to build up the saw guide face to the revised angle. This alteration was empirical, based on the appearance of the model. The osteotomy was then closed and the distal portion rotated to provide optimal joint alignment and glued into place with cyanoacrylate adhesive for later reference. A six-hole 2 mm dynamic compression plate was contoured and applied to the corrected model (Fig. 6). We felt it was important to contour the plate at this stage not only to save time during surgery but also to ensure we could recreate the reduction and rotation accurately in the patient. The PMMA saw guides and the two models underwent cold sterilisation with no adverse effects and the contoured plate was autoclaved.

Angular correction surgery was conducted with the dog under general anaesthesia and utilising a brachial plexus block. A standard hanging limb preparation was performed with the dog in dorsal...
recumbency. A limited caudo-lateral approach was made to the distal ulna and a releasing 3 mm ostectomy was performed approximately 20 mm from the tip of the styloid. A medial approach to the distal third of the radial shaft was performed. Using the intact model as a comparison, the periosteum was elevated over the area where the plate would be applied. The PMMA saw guides were manipulated along the radius until they matched its surface contour and were then held in place with pin-point reduction forceps (Fig. 7). As the guides had been created on the surface contour of the plastic model they fitted correctly in only the appropriate site for the osteotomy. Using the wedge created from the practise surgery as a comparison we confirmed we had outlined an accurate wedge in the correct place. The wedge was then cut with an oscillating saw using each edge of the PMMA guides to direct the position and plane of the blade. The sterilised acrylonitrile butadiene styrene wedge from the model was used as a direct comparison to the bone wedge, which showed we had replicated our planned osteotomy accurately. The saw guides were then removed from the radius and the ostectomy gap was reduced. Correction of rotation was aided by comparing the morphology of the reduced ostectomy on the model. The distal fragment was internally rotated approximately 60° and the pre-contoured plate helped ensure that our reduction accurately replicated the rehearsal surgery. The pre-contoured plate was then applied starting with the screw hole immediately proximal to the ostectomy. The distal fragment was then aligned with the contoured plate which ensured we achieved the same reduction as we had with the model. A total of six cortical screws were placed with three screws proximal and distal to the ostectomy site, using compression plating technique. We were satisfied with limb alignment and joint range-of-motion, thus we preceded to routine closure. A light dressing was placed over the surgical incision sites, but supportive external coaptation was not used. Gross observation of the limb in the immediate postoperative period showed an apparently satisfactory correction of the angular and rotational deformity. Cranio-caudal and lateral radiographic views were obtained, and when compared to the preoperative radiographs, showed that the rotational deformity of the radius was corrected. Using the CORA method, the medial proximal radial angle (MPRA) was 80° and the lateral distal radial angle (LDRA) was 75°, giving a mean frontal plane angle of 5°. Fox et al reported a mean (± SD) MPRA of 85.3 ± 3.5° and a LDRA of 86.7 ± 2.9°, giving a range for frontal plane angle of 0–8° in a study of the antebrachiae in medium to large breed dogs (7). The postoperative proximal cranial radial angle (PCRA) in our patient was 89° and the distal cranial radial angle (DCRA) was 76° (Fig. 8). By comparison Fox et al found a mean (± SD) PCRA of 90.5 ± 4.0° and a DCRA of 78.3 ± 4.8° in their study. Our patient had a mean sagittal plane angle of 13° after correction, which is within the reported range for natural procurvatum of 8 – 35° (7) There was a translational shift induced by the single level osteotomy. Comparison of the preoperative antebrachium with a postoperative 3D CT reconstruction could have quantified the extent of correction achieved versus that planned. However, due to the anticipated artefact that would have been caused by the implants, a CT scan was not performed. The postoperative appearance of the limb is shown in Figure 9.

**Fig. 4** Illustration of the corrective wedge ‘removed’ as a simulation of the proposed surgical method (left image) then reduced by image manipulation to close the wedge and rotate the distal fragment, simulating the intended surgery (right image).

**Fig. 5** A) A stereolithographic model was created in acrylonitrile butadiene styrene (ABS) by Fused Deposition Modelling including the planes used to define the ostectomy wedge. B) Polymethylmethacrylate (PMMA) was built up on either side of the planes, cold sterilised, and then used as surgical saw guides.
bone healing under a stable compression plate fixation. The dog’s activity levels were altered starting with five minute lead walks twice a day, and increasing this by five minutes every 14 days.

Three months after the procedure the owners reported there were significant positive changes to both the dog’s ability to exercise and its quality of life. The dog was no longer lame and did not buckle at the carpus when walking, though it still exhibited a gait imbalance which was attributed to the as yet uncorrected right forelimb. The dog’s activity level was uninhibited and the owners reported they were very satisfied with the appearance of the leg. Radiographs taken 12 weeks after surgery indicated progressive primary bone healing of the radial ostectomy and an atrophic non-union of the ulnar ostectomy (Fig. 10). A telephone follow-up at six months confirmed that the owner had not observed any complications and the dog had increased mobility and exercise tolerance without buckling over.

Postoperative care

The dog recovered from anaesthesia without complication and buprenorphine\(^8\) (0.03 mg/kg, subcutaneously TID) and carprofen\(^b\) (1.5 mg/kg per os, BID) were administered for analgesia. The dog was discharged after three further days and the owners were instructed to ensure the dog remained confined with only short lead walks for toileting for six weeks. The dog was re-evaluated six weeks after surgery and there was not any evidence of complications. There had been suitable owner compliance with adequate exercise restriction. Radiographs showed slow progression towards bony union at the osteotomy site and the implants were static in position. This was consistent with primary

Discussion

We describe a novel method for accurate planning of a closing wedge osteotomy in 3D using CT and computer software. Rapid prototype modelling was then used to create models for saw guide fabrication, pre-contouring of the plate and rehearsal surgery. The patient had a successful outcome with greatly improved limb use and cosmetic appearance. Future carpal degeneration may be reduced by improvement of the loading through the carpus.

The decision to use CT in the planning of this case arose from the desire to use internal fixation with a bone plate as opposed to external skeletal fixation. Both techniques can be successfully used for ALD, however complications, especially postoperative infections are greater when an external skeletal fixator is used (12–13). External fixation allows postoperative adjustment of the construct; therefore the original osteotomy does not need to be as accurate. However, external skeletal fixation has a longer period of postoperative morbidity and the requirement for frequent rechecks. In contrast, this patient was effectively treated with a one-stage procedure and there was minimal postoperative morbidity and the requirement for frequent rechecks. In contrast, this patient was effectively treated with a one-stage procedure and there was minimal postoperative morbidity with rapid and improved limb use. Plating of a distal radial osteotomy in a single-stage procedure may be associated with greater risk of over or under correction as there is not any chance for adjustment in the postoperative period. This dog’s small bone size would have made accurate external skeletal fixation pin placement imperative, and any pin loosening could not have been easily revised. As a bi-radial saw blade sufficiently small for this patient was not available in the author’s hospital, a wedge technique with a straight saw blade had to be employed. We determined that the proximal

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\(^{8}\) Rimadyl, Pfizer Animal Health, Auckland, NZ
\(^{b}\) Temgesic, Reckitt Benckiser Healthcare (UK) Ltd, Hull, UK
deformity was minor compared to the distal radial deformity, therefore chose a single corrective osteotomy instead of a two-level correction as has been recommended for biapical deformities (7). The postoperative result was good with correction of the major deformity, but translation was present due to the single-level correction. Despite using two-level corrections, only 44% of dogs were corrected in both the frontal and sagittal plane in one study although it is not clear whether alignment of the elbow and carpal joint centres is important clinically to prevent eccentric loading leading to osteoarthritis (7). Therefore the authors believe a one-level correction was valid in this case.

In order to accurately perform a single closing wedge osteotomy, we used 3D CT and rehearsed the surgery electronically with engineering software. The data were then used to create stereolithographic models in plastic which could be handled by the surgeon, trial cut and glued to allow pre-contouring of the plate. This then improved the intra-operative accuracy of the de-rotation as the fragments were aligned by the plate to the same angulation as the model. The use of 3D CT data to simulate a proposed surgery with design software has not been reported before in veterinary surgery. Computer simulation has been described in human surgery, and has been used for corrective osteotomies for the treatment of cubitus varus and upper limb malunited fractures (15, 16). Use of computer simulation allows a surgeon to trial a range of potential osteotomies and to assess the optimal site and angle of correction. Once we were satisfied with the selected osteotomy, we could then create a model with the cutting planes and locations built into the model. After reading reports from human surgery, we decided to create our own simple cutting guides by moulding PMMA onto the plastic model abutting our outlined cut planes. This improved the accuracy of the rehearsal and subsequent surgery. Rather then visually translating measurements from the CT data, the location and angle of the osteotomy were determined by the saw guides that were held rigidly into position on the patient’s radius.

It is reported in human surgery that creation of a cutting guide template from a model and surgical simulation overcomes the inaccuracy associated with translation of the rehearsal surgery to the patient (16). Accuracy of the osteotomy is determined by the CT data resolution (±1 mm) and the accuracy of the reproduction of the model (±0.18 mm) rather than the surgeon’s intra-operative measurements and judgment. Our simple guides aided the use of the oscillating saw and illustrated how a specifically designed template or jig would be a great advantage.
Stereo-lithographically produced jigs can be fabricated from plastic or metal as shells and used in the same manner as the PMMA guides used in this case. With greater familiarity with the technique, the surgery could be rehearsed electronically, and then the saw guides themselves can be printed without the direct requirement for the bone models. The use of specifically manufactured surgical templates is an area which requires further study but should have application in veterinary surgery.

The method used in human surgery known as CORA has been promoted for the preoperative measurement of the site and angle of corrective osteotomies (4, 7, 11, 17). However this method is based on orthogonal radiographs and thus only two isolated axes can be identified; the lateral and cranio-caudal axes. The authors also found it difficult to isolate the true anatomical orientation of both the proximal and distal radial joint surfaces. Identifying the joint orientation was especially complicated at the distal radial surface. Due to the deformity there was superimposition of the radialcarpal and accessory carpal bones with the distal radius, and carpal rotation, obscuring the normal radiographic landmarks. It may have been possible to use the segmental radiography method outlined by Dismukes et al (2008) to avoid the superimposition of the carpal bones and the radius caused by rotation (11). However, as this method is still two-dimensional, it was decided to use 3D CT to augment and improve our understanding of the deformity within the radius. To compare traditional CORA measurements on orthogonal radiographs with the wedge as defined by the CT data, we radiographed the models. It was difficult to truly replicate the dog’s limb as the elbow of the model was fixed. However, it was clear that these two methods of measurement yielded different results with regard to wedge angle and orientation.

The use of 3D CT reconstruction to identify the true orientation of joint surfaces with a view to applying the CORA methodology has not been previously described in animals. Meola et al used CT data to assess radial torsion in the presence of procavum and valgus deformity in dogs using cadavers (8). The use of CT has also been validated for the assessment of human radial torsion (18). In orthopaedic surgery, a similar technique to the one used in this report has been described, but instead of estimating a normal for the curvature of the bone from the joint surface, the contralateral limb was used as a guide (15). In this case, the contralateral limb was also affected by rotational and angular deformity, therefore this method could not be used to replicate the normal anatomy. Although we felt our method was an easier and more accurate way of joint surface angle measurement, this is purely a subjective observation. We lacked sufficient data to aid our decision on what a ‘normal’ trajectory from the joint surface should be in each of the three planes, therefore an arbitrary value of 90° from the joint surfaces in all axes was used. Fox et al has described the mean MPRA as 85° and the mean LDRA of 87° in the frontal plane (7). Mean torsion in the transverse plane calculated from three dogs was 4.88° (8). However these data were obtained from radiographs and has not been determined for CT reconstructions. Additionally, these data were obtained from medium to large, non-chondrodystrophic dogs, and as noted, these angles are likely to be variable by breed (7).

Studies using 3D CT to accurately determine the lateral and cranio-caudal planes and degree of torsion would be very useful to guide future computer assisted surgeries for Ald. The major limitation of this study is that it was a first attempt with the proposed method. Both unfamiliarity with the capabilities of the software systems and the lack of normal data both contributed to the flaws in the method we report. However with further work, it will be easier to determine whether this method is primarily valid and how it relates to previously described methods of radiographic measurements. After rehearsing the surgery, with both the engineering software and the model, it was clear that the correction using these 90° trajectories would create an antebrachium which was completely straight. We felt that complete correction of the procavum was not desirable and as a result the saw guides were modified to reduce the correction and leave a degree of cranial bowing. Although this adjustment was empirical it was based on the already defined wedge and so was performed with confidence and the changes could be rehearsed. Ideally, a surgeon would have access to normal axes, as determined in 3D from an unaffected contralateral limb, or obtained from measurements from several individuals of the same breed description. These data are currently lacking.

The use of CT data to create stereolithographic models to aid surgery is widely reported in the human literature and early reports are in the veterinary literature (11, 19–22). It has had greatest application in cranio-maxillofacial surgery but is also being used within many areas of orthopaedic and now cardiovascular human surgery (23–25). Models can be used to rehearse surgery, contour implants, improve diagnostic abilities, and aid understanding both by the clinicians involved and the client. Human studies have concluded that the use of stereolithographic bio-models in combination with standard imaging ‘have greater utility in surgical management than the standard imaging data alone’ (23). It is also reported that surgeons feel the use of bio-models reduces time for surgical procedures, although due to the inability to repeat a surgery with two methods, this observation is purely an anecdotal finding (21, 23). We certainly found that having the models was very valuable in the planning of the case not only for the procedure itself but also explaining the procedure to the owner.

This case report shows the use of this new technology is applicable to veterinary surgery and that it is possible to improve the accuracy of surgical procedures involving complex geometry. It does however highlight the need for further study. Three-dimensional CT data from dogs unaffected by antebrachial deformity needs to be collected to provide a ‘normal’ data set so as to provide a guide for correction. Additionally, a comparison of the results achieved using radiography versus CT is needed to assess whether the extra cost of CT and modelling is warranted.

Following this surgery, we concluded that the additional information gained with advanced imaging, stereolithographic models and our basic saw guides did benefit the patient. These methods were intuitive and greatly increased our knowledge.
of the morphology of the deformity, aided client communication, raised surgical confidence and potentially increased surgical accuracy whilst decreasing surgical and therefore anaesthetic time. We propose that computer assisted surgery offers the veterinary orthopaedist many advantages and warrants further investigation.

References


