ANGULAR LIMB DEFORMITIES AFFECTING THE CANINE RADIUS AND ULNA: CLASSIFICATION USING THE CENTER OF ROTATION OF ANGULATION METHOD

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by

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
aCdDRA	Anatomic caudal distal radial angle
aCdPRA	Anatomic caudal proximal radial angle
ALD	Angular limb deformity
aLDRA	Anatomic lateral distal radial angle
aMPRA	Anatomic medial proximal radial angle
CORA	Center of rotation of angulation
CT	Computed tomography
ESF	External skeletal fixator
JOL	Joint orientation lines
OA	Osteoarthritis
θ	Angular intersection of 2 segmental joint reference axes

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ABSTRACT

We hypothesized that 1) antebrachial ALDs would be more complex with respect to multiplicity in chondrodystrophic dogs, and 2) more complex ALDs would exhibit a higher incidence of concurrent joint radiographic disease. Medical records from 2006 to 2013 were searched and cases included of dogs diagnosed with thoracic limb lameness attributable to antebrachial ALDs with orthogonal radiographs or CT scans of the affected antebrachium. Classification of the deformity in the frontal plane, and the presence of sagittal plane angulation, torsion, and adjacent joint radiographic disease were determined and compared. Thirty-five uniapical, 70 biapical, and 1 multiapical deformities in the frontal plane were identified. The incidence of biapical deformities was statistically higher in chondrodystrophic versus non-chondrodystrophic dogs (P = 0.02). When breeds were combined, biapical deformities were associated with a significantly higher incidence of adjacent joint radiographic disease (P = 0.049); more frequently resulting in elbow disease (P = 0.022). Overall, 82% of the 106 limbs had radiographic evidence of either elbow or carpal joint disease at the time of presentation. In dogs with limb deformities, particularly chondrodystrophic dogs, biapical deformities are common. Adjacent joint radiographic disease should be evaluated in all patients presenting for antebrachial deformities.

CHAPTER 1: LITERATURE REVIEW

The first antebrachial angular limb deformity was reported in a 5 month old Weimaraner by a radiologist at the University of Minnesota.[1] Not only did she report radiographic closure times for the ossification centers of skeletally normal dogs, Dr. Hanlon described seven cases of various abnormal bone growth and development.[1] The Weimaraner reportedly had an injury at two months of age to a forelimb, which when radiographed at five months of age, appeared to have premature closure of the distal ulnar physis and subsequently a classic antebrachial angular limb deformity.[1] The deformity was labeled dyschondroplasia of the radius, ulna, with rachitis or radius curvus.[1]

In 1963, a report summarized normal extremity physeal histology in children and provided a classification system for injuries near the physis.[2] The paper described the difference between pressure and traction physes. The former located at the end of long bones, subjected to stresses through the joint, and primarily responsible for longitudinal growth of the bone. In contrast, traction physes are located at sites of attachment of major muscle tendons to the bone, subjected primarily to tensile forces, and contribute more to bone shape than longitudinal growth of the long bone.[2] The microscopic anatomy of these physes includes: the resting zone of chondrocytes; proliferating zone of chondrocytes; hypertrophic zone where calcification and apoptosis occur; and the zone of vascular ingrowth and primary bone formation. Injuries to the physes consist of separation of the physis primarily at the hypertrophic zone, fracture across the physis, and crushing injuries.[2] Disturbance of the blood supply along with crushing of the physis can lead to a cessation of growth of the bone by pressure physes. The extent of deformity due to premature closure of a growth plate depends on the bone involved, remaining growth potential, and extent of involvement of the physis.[2] Injury to a paired bone (radius, ulna, tibia, or fibula) or cessation of just a portion of the physis with continued growth of the remaining portion will lead to progressive angular limb deformities.[2]

In addition to this review of physeal injuries, Salter and Harris proposed a classification scheme of physeal injuries that is still used today in the medical and veterinary field. The Salter-Harris physeal fracture classification was based on the mechanism of injury and the relationship of the fracture line to the physis.[2] It also was an attempt at prognosticating the future disturbance of growth.[2] They stated that Type I (separation of the physis), II (fracture of the metaphysis and physis), and III (fracture of the physis and epiphysis into the joint) injuries had a better prognosis at continued growth if the blood supply was maintained.[2] Type IV injuries (through the metaphysis, physis, and epiphysis into the joint) had an overall poor prognosis at that time unless the physis could be completely realigned.[2] Crushing injuries of the cartilaginous plate (Type V) lead to complete cessation of that portion of the physis and thus grave prognosis for continued longitudinal growth.[2] While this fracture classification scheme is still used in veterinary medicine, the Salter-Harris scheme does not necessarily correlate with prognosis of the joint and continued growth potential as it did not categorize based on blood supply as well.

O'Brien et al in 1971 reviewed growth disturbances in the forelimbs of 35 dogs.[3] Giant and large breeds accounted for 26% of the cases and the average age at the time of injury was 4 months.[3] It had a detailed account of the radiographic changes noted with premature closure of the canine distal ulnar; distal radial; both distal ulnar and radial; and the proximal radial epiphyses.[3] The prevalence of each premature closure was disproportionate with 74% of the cases presenting with distal ulnar physeal premature closure; 11% with distal radius; 9% with both distal radius and ulna; and 6% with proximal radial premature closure.[3] The authors not only discussed the discrepancy in bone length and angulation, but they also described the radiographic disease within the adjacent joints.[3] Varying degrees of elbow incongruity, subluxation, and osteoarthritis along with carpal subluxation and mild carpal osteoarthritis were noted in some of these cases, on average 5-7 weeks after their traumatic injuries.[3] They concluded that physeal injuries that cause an interference with endochondral ossification could produce a deformity and shortening of the forelimb and secondary osteoarthritis.[3]

A measurement of the amount of angulation in the distal radius/ulna to the carpus was performed in 25 skeletally normal dogs as well in this study.[3] The assessment was adapted from a lining system used in the wrist of people from radiographs to determine proper axial relationship of the wrist.[3] On the craniocaudal radiograph of the carpus including the distal antebrachium, a line was drawn perpendicular to the space between metacarpal III and IV and a second line was drawn connecting the styloid processes of the radius and ulna.[3] The angle formed from these two lines was determined to be the angulation in the carpus at 0-10°.[3] The second angle measured was taken from the lateral radiograph of the carpus. A line perpendicular to the middle of the radial carpal bone was drawn along with a line through the radiocarpal joint. The angle was determined to be 0-8° in these normal dogs.[3] This group of radiologists felt the degree of deformity should be measured from radiographs, especially if surgical correction was planned.

A congenital form of premature distal ulnar physeal closure was described in a group of Skye terrier puppies.[4] Due to selective breedings, it was discovered that this abnormality was a recessively inherited genetic trait in this breed.[4] Twenty of these 23 related dogs had clinical lameness noted and the trait was variably expressed.[4] Radiographic changes noted in these dogs included lateral subluxation of the radial head, medial bowing of the ulnar shaft, elbow incongruity, and varying degrees of arthritic changes.[4] They discovered that the sooner the physis closed, the more severe the secondary elbow osteoarthritis noted.[4]

Antebrachial growth is complex in that the radius and ulna must develop in a synchronized manner to maintain the common articular surfaces of both carpus and elbow. All growth distal to the elbow occurs at the level of a singular distal ulnar physis matching that of two physes of the radius.[5-7] A study where Kirschner wires were placed within various diaphyseal regions of the radius and ulna in four Australian shepherd puppies revealed that approximately 40% of the length of the radius was the result of the proximal radial physis and 60% from the distal radial physis.[6] The radial proximal growth plate closed before the distal radial physis and this accounted for the mild discrepancy between the contributions of longitudinal bone growth by the two physes. In order for both bones of the antebrachium to develop simultaneously in large and giant breeds, the distal ulnar physis exhibits accelerated longitudinal growth with its conical shape (providing more surface area for endochondral ossification) and a wider diameter of the entire ulnar shaft in comparison to the radius, that diminishes as growth slows in these dogs.[5, 8] Any disruption of either radial physis or, more commonly, the distal ulnar physis can lead to asynchronous growth of the radius and ulna causing deformity of the limb.[3, 9, 10] In 1979, an experimental study administered radiation therapy to the distal radial physis of eight, 70-day old dogs.[11] It found that even with damage to the distal radial physis and distal ulnar physis (due to proximity) with irradiation of the cells, there was an accelerated longitudinal growth by the proximal radial physis that minimized subluxation of the humeroradial joint.[11] There was an even more complex relationship between the radius and ulna that helped minimize the deleterious effects of elbow joint incongruity and angular limb deformity in this experimental model.[11]

Skaggs et al in 1973 described the unique conical shape of the canine distal ulnar physis.[7] The shape predisposes this particular physis to premature closure, due to an inability to shear.[7, 10] With axial or lateral forces placed on the thoracic limb, a shearing force is transformed into a compressive force on one side of the physeal cone, ultimately interfering with endochondral ossification at the site.[7, 10] Fourteen dogs with a history of trauma had premature distal ulnar physeal closure in the report by Skaggs et al from a clinic in New York City.[7] Thirteen of the 14 dogs were labelled as medium or large breed dogs, though size was not stated to be a risk factor for premature closure of this conical growth plate.[7] Potentially this correlation was overlooked considering most of these cases had vehicular trauma, which off leash larger dogs may be at a higher risk of encountering in a big city.

The relatively high incidence of premature closure of the ulnar physis in large and giant breeds was again highlighted in a case series by Ramadan and Vaughan in 1978.[8] Over a 2-year time period, 92 dogs with a physeal disorder of bone growth were identified, for which 58 dogs (63%) specifically had premature closure of the distal ulnar growth plate in at least one forelimb.[8] They found a predominance of dogs > 25 kg, accounting for 46 of the 58 dogs.[8] Great Danes accounted for 25% of the cases with premature closure of the distal ulnar physis.[8] There was a higher number of male dogs (n = 12) in comparison to females in this group of 15 Great Danes as well.[8] They identified most patients with an angular limb deformity at 4-6 months of age.

Ramadan et al proposed two methods for measurement of the radio-carpal angle.[8] The first method positioned the dog on its sternum with the forelimb extended over a long sheet of paper. Points were marked on the paper next to the tip of the olecranon, the accessory carpal bone, and the nail of the 3rd digit.[8] The line created by connecting the accessory carpal bone to the olecranon dot was extended distally. The angle created from the third digit to the accessory carpal bone to the extension of the "antebrachial" line was labeled as the radio-carpal angle.[8] The second method proposed using a customized goniometer the authors built for an automatic reading of the previously described angle.[8] The degree of carpal valgus calculated varied from 5-35° in these affected 58 dogs, using this methodology.[8]

Physeal stapling, placed medially, providing selective compression of the open distal radial physis was the surgical treatment of choice in most of these cases. Staples made of Kirschner wires or Steinman pins, depending on the patient size, were placed across the medial distal radial physis in 49 limbs.[8] Eight had concurrent ulnar osteotomy performed to release the ulna from the lengthening radius.[8] Stapling was successful in correcting the valgus deviation in 39 out of 49 limbs (80%).[8] Recommendations were made to have the staple tines approximately half the width of the bone to prevent compression of the entire growth plate. The theory behind stapling of the physis was that it worked to slow endochondral ossification to allow the remaining portion of the physis to “catch up.” An experimental study in 2013 using 6-week-old rabbits placed physeal staples and found that the area ratio of each layer of the physis decreased every week in comparison to the other side.[12] Of the three layers that make up the physis (resting, proliferative, and hypertrophic layers), in this study they identified that the area of proliferating chondrocytes decreased the most of the layers of the physis.[12] The hypertrophic zone was suppressed, but not as much as noted in the proliferative zone of chondrocytes.[12]

Ramadan et al reported that loose or misplaced staples appeared to not allow some limbs to improve in angulation, so corrective osteotomies of the radius and ulna were performed in 8 limbs. The study reports that the size of the wedge removed was based on an assessment of the radiographs.[8] Another case report from 1972, reported success in straightening of an antebrachium in a 3 month old Great Dane using two physeal staples.[13] No objective measurements were reported though, and subjectively looking at the three provided lateral radiographs of just the distal radius/ulna and carpus, the procurvatum angulation appears similar if not mildly worse.[13]

Premature closure of the canine distal radial physis was discussed by both Olson et al in 1980 and Vandewater and Olmstead in 1983. Some of these cases had simultaneous premature closure of the distal ulnar physis (n=3) and proximal radial physis (n=1).[14] The angular limb deformities that subsequently occurred were more noticeable with asymmetrical closure of the distal radial physis in comparison to a complete closure of the physis.[14, 15] While both types of physeal closures had a short radius and widened humeroradial space, a valgus deformity of the carpus in relation to the radius/ulna was only noted in those with asymmetric closure of the distal radial physis.[14, 15] Olson et al described two surgical techniques for correction of the abnormalities noted.[15] In both cases, an opening transverse radial osteotomy was stabilized with a bone plate and screws to correct the humeroulnar incongruity.[15] For the patient with angulation, a staged procedure with a cuneiform radial osteotomy stabilized with a Kirschner apparatus was done 8 weeks later.[15] The wedge removed was created with a proximal cut parallel to the proximal radial physeal scar and a distal osteotomy parallel to the distal radial physeal scar.[15] Vandewater described resection of the abnormal bone bridge associated with a partially closed radial physis with placement of a fat graft to release the remaining open distal radial physis.[14] In these dogs, the angular deformity was corrected with an oblique osteotomy of the radius and stabilization with a Kirschner-Ehmer external fixator.[14]

A retrospective study from the Animal Medical Center in 1983, identified angular growth deformities in 9 of the 135 dogs (7%) they found to have physeal injuries.[16] Of the 12 cases categorized as Salter-Harris Type V crushing physeal injuries, eight had clinically evident angulation to their long bones; seven requiring surgical correction to straighten the limbs[16] The most common physeal injury leading to these angulations was the distal ulnar Salter-Harris Type V injuries (n = 6).[16] In addition, there was a case each of the following physeal injuries that lead to angular limb deformities: a Salter-Harris Type V of the distal femur and a distal radial Salter-Harris Type II and Type V.[16] The amount of angulation within the antebrachium was severe enough that surgical correction with an osteotomy was necessary in all 8 of the previously described antebrachial physeal injuries.[16] Due to the preponderance of Salter-Harris Type V injuries that lead to severe angulation within the long bone, Marretta and Schrader concluded that the Salter-Harris classification scheme was clinically applicable to prognosis of physeal injuries.[16]

The justification of using the Salter-Harris physeal classification scheme in regards to prognosis of long bone continued growth in dogs was examined in a group of puppies with physeal fractures where euthanasia was elected.[2, 17] Histopathologic evaluation of the physeal fractures was performed in a total of thirteen fractures.[17] They represented 10 Salter-Harris Type I fractures, and one of each of Salter-Harris Type II, III, and V fractures.[17] Histologically the fracture lines were identified through: the junction of the hypertrophic zone (as predicted by the Salter-Harris paper); zone of provisional calcification; metaphyseal cancellous bone; resting zone; and epiphyseal bone.[2, 17] Overall, this study found that fractures of the physis in experimentally created animals, may not be occurring in the same location within clinical cases.[17] They also found that a lot of the fractured physes had extensive damage to the proliferating cells whether these chondrocytes were attached to epiphyseal bone or not.[17] Radiographic classification of a naturally occurring physeal fracture by the Salter-Harris system did not always correlate with the predicted histological appearance by Salter and Harris.[2] After any traumatic event, they recommended a guarded prognosis for continued physeal function until the clinician could radiographically monitor the bone in the future and see continued elongation at that site.

A report from Shields Henney and Gambardella in 1989, offered a different surgical technique used by itself to help correct premature distal ulnar physeal closure with remaining radial growth potential. Within a group of 34 surgical canine cases, 26 had a partial ulnar ostectomy performed.[18] Unsatisfactory results were noted in only four cases that lead to a radial cuneiform ostectomy for correction of the deformities.[18] Either the distal ulnar physis or the distal ulnar diaphysis was removed.[18] Some had an autogenous fat graft placed, and some had stabilization provided by an intramedullary pin within the ulna, depending on surgeon preference.[18] Measurements of carpal valgus were taken from radiographs, though the exact methodology was not clear from the article. A classification scheme as to the severity of carpal valgus was proposed: 0-12° = mild; 13-25° = moderate; > 25° = severe.[18] They found that puppies with severe angulation, regardless of radial growth potential benefited more from both a radial cuneiform osteotomy and proximal ulnar ostectomy at the first surgical intervention.[18] Shields Henney et al, did feel a partial ulnar ostectomy could correct the problem of angulation in those puppies with mild valgus.[18] They also diagnosed, on follow up radiographic studies, degenerative changes within the elbow and carpus of moderate to severe angular limb deformities that were not corrected.[18]

A review of torsion within quadrupeds and the impact on their joints was published in 1994.[19] In addition to discussing foals, congenital torsional deformities in puppies and kittens was noted to exist, though Turner stated that specific characterization of these cases was not well documented.[19] Torsion of the limb or bone was treated throughout the paper as a separate entity from an angular limb deformity. Outward torsional defects were stated to commonly occur within patients with carpus valgus and inward torsion concurrently with carpus varus.[19] They reported that premature closure of the distal ulnar growth plate of dogs often had evidence of cranial bowing of the radius (radius curvus), lateral deviation at the level of the carpus, humeroulnar subluxation, and external rotation/torsion of the distal radius to paw.[19] After describing the common medial deviation at the carpus and inward rotation/torsion of the distal thoracic limb with premature closure of the distal radial physis in dogs, Turner states that "torsional deformities after trauma in domestic animals are rare."[19] Torsional deformities within foals had been associated with predisposition to degenerative joint disease in athletic patients, though no statements were made in regards to joint disease within small animal patients with torsion noted.[19]

An article within the Orthopedic Clinics of North America by Dror Paley revolutionized the classification of angular deformities in the frontal and sagittal planes to help with planning corrective osteotomies.[20] This paper was in regards to people with angular limb deformities of the femur and tibia.[20] It went step by step how to identify and classify the degree of deformities found in these limbs with Paley's schematic of the Center of Rotation of Angulation (CORA) Methodology.[20] Paley stressed the importance of preoperative planning of corrective osteotomies with objective measurements from well positioned radiographs or positioning of the patient during examination.[20] This manuscript, a decade later, expanded into an entire book that is used by both human and veterinary orthopedic surgeons today.[21]

Components of Paley's technique were applied to veterinary patients by Marcellin-Little et al in 1998.[22] He found that all of the dogs in a series of seven had their deformity in an oblique plane from the frontal and sagittal planes.[22] The authors explained that a deformity was described by its amplitude, direction in relation to the frontal plane, and point of origin in the sagittal plane. The graphical method of planar deformity was first adapted from Paley's work to locate the magnitude and direction of the oblique plane of deformity in these 7 dogs.[22] The contralateral limb of unilateral angular limb deformities was also recommended as a template when planning the surgical correction.[22] Without an unaffected side, the radius of a normal dog of similar size, breed, and age was used as a reference for the goal with correction.[22]

After objective measurements of the deformity, all 7 cases within this series had a hinged Ilizarov external skeletal fixator utilized for progressive correction of the angulation within these antebrachii.[22] The rotational (torsional) deformity was acutely corrected at the time of radial osteotomy and application of the circular skeletal fixator.[22] Due to cosmesis and the first ulnar osteotomy healing too quickly in these patients, an ulnar ostectomy with a radial osteotomy was recommended when using a hinged circular external skeletal fixator.[22] Each case within the series had a good to excellent outcome in regards to owner satisfaction, an orthopedic examination, and radiographs of the operated limb per the authors.[22] A linear motor fixator had also been discussed in a single case for a dynamic corrective transverse mid-diaphyseal radial osteotomy.[23] This Wagner apparatus helped encourage distraction osteogenesis to account for a limb length discrepancy.[23] Using circular skeletal fixators for an acute correction of angular antebrachial deformities was described by Welch and Lewis around the same time.[24]

More recently, an article from Captug and Bilgili compared antebrachial deformities of 7 dogs whose correction was stabilized with a circular external skeletal fixator.[25] Three cases had the fixator and motor placed after a transverse radial osteotomy to provide a progressive correction of the angulation within the radius and ulna while also encouraging distraction osteogenesis to resolve a limb-length discrepancy in these patients.[25] Whereas the other four cases had an acute correction of their radial angulation with a closing wedge ostectomy of both the radius and ulna.[25] After a latent period, a linear motor was utilized to encourage resolution of the limb-length discrepancy.[25] In both the abstract and conclusion of the article, an acute correction was offered to "provide a faster, better, and more practical treatment option" for management of antebrachial angular limb deformities over a progressive correction with similar equipment after a radial osteotomy.[25] This recommendation though is not based on any direct comparison of outcome or complications encountered between the two groups of patients.[25]

In 2000, Quinn et al published a clarification for measurement of the degree of varus/valgus deformity by measuring the angle between lines drawn perpendicular to and bisecting the radiohumeral joint and radiocarpal joint on the frontal radiograph.[26] A similar technique was used on the lateral radiograph to measure the amount of angulation in the sagittal plane.[26] Quinn et al's case series of 28 dogs had an acute opening wedge osteotomy of the radius and ulna stabilized with a type II external skeletal fixator.[26] Stabilization by internal fixation with a 2.7/3.5 mm ASIF T-plate for a closing wedge ostectomies of the distal radius.[27]

A prospective clinical study in 2005 from the Netherlands followed 34 dogs with unilateral antebrachial angular deformities.[28] They had 2 chondrodystrophic dogs out of their group. Rotational (assume torsional) deformity was present in 44% of the cases.[28] They identified arthritis in 50% of the elbows and 35% of carpi at initial presentation; both elbow and carpal OA were noted in 14% of the patients.[28] Joint osteoarthritis worsened significantly in both elbow and carpus at follow-up appointments.[28] Worse elbow osteoarthritis at the time of initial presentation was more likely to be correlated with more severe lameness at final follow up.[28] Older patients that were evaluated and treated surgically had more severe elbow OA at follow-up too.[28] Twenty-five dogs had a closing wedge osteotomy stabilized with a circular external skeletal fixation system and 10 had a dynamic correction with a hinge and angular motor.[28] For placement of the radial osteotomy, the center of the deformity was subjectively assessed.[28] In this prospective clinical study, it was identified that osteoarthritis was a major factor in outcome.

Further application of the CORA methodology from Paley was proposed for use in canine patients by Fox et al in 2006. Instead of using perpendicular lines down the axis of the bone in relationship to a line representing the joint, determination of normal joint orientation angles were calculated in 20 non-chondrodystrophic adult dogs without musculoskeletal disease.[29] More specific anatomic landmarks were described for repeatable orientation of joint orientation lines for the carpus and elbow in both the frontal and sagittal planes.[29] Limb classification of angular abnormalities in regards to severity was also described by the number and relationship of multiple CORAs found within the bone using the methodology described.[29] In this case series of 9 limbs, a dome osteotomy with internal stabilization was described for correction of their deformities.[29]

The use of a segmental orthogonal radiographic technique to assess the complexity of the deformity within the bone, was described two years later.[30] The joints were used as references in this application of the CORA methodology, hence the importance of radiographs focusing on the orientation of the joints. In addition, this case report of a partially compensated, biapical antebrachial deformity had computed tomographic imaging and a stereolithographic model created of the radius and ulna to help with preoperative planning.[30] Two closing wedge radial ostectomies were performed on this patient to address both CORAs within the antebrachium.[30]

A prospective, non-randomized cohort study described 13 patients with biapical radial deformities.[31] All patients had a partially compensated biapical deformity of the antebrachium.[31] They all had severe varus of the proximal aspect of the radius with concurrent severe valgus angulation of the distal radius and severe radial torsion that lead to carpal buckling during ambulation.[31] They described a proximal and distal radial osteotomy with an acute torsional correction and stabilization with a bi-level hinged circular ESF.[31] The angulation within these antebrachii was corrected progressively at both locations of the radius with concurrent distraction osteogenesis via motors on the ESF.[31] Only one dog had radiographic and CT evidence of arthritis within the elbow joint.[31] They did report 93% of limbs had lateral radial head subluxation.[31] The carpal buckling was not observed in any cases after surgery and subjective lameness scores improved post-operatively.[31]

In regards to imaging of these patients, an anatomic study from 2008 looked at computed tomography accuracy of measuring induced torsion of the radius with varying degrees of procurvatum and valgus.[32] A method to measure torsion (angulation in the transverse plane) was described using superimposition of CT images at the level of the proximal and distal physeal scars.[32] Specific boney anatomic landmarks were again described to quantify the amount of torsion noted within the radius. Using this proposed method, two observers had a high correlation of calculation of external torsion within radii.[32] Torsion alone is rare to find in clinical cases, thus Meola et al assessed repeated calculation of external torsion in radii with concurrent excessive procurvatum and valgus.

They discovered reproducible and accurate measurements of radial torsion up to 40° of excessive procurvatum and valgus at a single location within the radius.[32]

In a similar study by Piras et al in 2012, evaluated the effects of antebrachial torsion on calculations of induced valgus angulation on radiographic images.[33] After inducing 30° of external torsion, there was a significant miscalculation of the magnitude of valgus present.[33] This miscalculation was not noted with 15° of external torsion of the antebrachium.[33] The second part of the study looked to validate the use of the previously described segmental orthogonal radiographic technique that focuses radiographic images in regards to the joints, ultimately repositioning the limb to mimic the degree of external torsion.[33] They found that this technique resulted in a high correlation between the true amount of valgus induced and the calculated value from the radiograph within 5° of error.[33]

Fitzpatrick et al reported a case series of 35 canine antebrachial limb deformities that had an acute correction at the most distal CORA within the radius via a transverse opening wedge osteotomy.[34] These surgical corrections were stabilized with a double-arch modified type 1b ESF.[34] The frontal plane classification scheme adapted from Fox et al was not applied to these limbs, but the CORA methodology to objectively quantify the magnitude of the deformities was performed.[34] All cases were lame preoperative with evidence of external torsion and excessive radial procurvatum.[34] Though not a major aspect of their study, manipulation of all ipsilateral elbows revealed pain and humeroulnar subluxation was radiographically noted in 16/35 elbows (46%).[34]

A report from 2014, described not performing pre-operative planning in 39 dogs with radial procurvatum, torsional deformity, and "carpal" valgus.[35] They performed a closing cuneiform radial ostectomy, distal ulnar ostectomy and stabilized with a type 1b ESF.[35] They used alignment noted within surgery as the standard for correction.[35] Post-operative assessment was determined through client phone interview as to their experience and their pets functionality.[35] Owners stated that limb function was excellent in 67% and good in 31% of cases, and the authors concluded their simpler technique resulted in good clinical results.[35]

CHAPTER 2: INTRODUCTION

Antebrachial Angular Limb Deformities

Angular limb deformities (ALDs) commonly affect the canine radius and ulna. To date, the largest reported series of dogs presenting with antebrachial deformities is a study completed by Ramadan et al in 1978.[8] This report described 58 cases of radial angulation attributable to premature closure of the distal ulnar physis that were presented to the Royal Veterinary College over a 2 year time period.[8] Approximately 80% of the dogs were > 25 kg and Great Danes represented 25% of the cases.[8] At the time, no classification system existed to more completely describe the frequency of various subtypes of antebrachial deformities.

Antebrachial growth is complex in that the radius and ulna must develop in a synchronized manner to maintain the common articular surfaces of both carpus and elbow. All growth distal to the elbow occurs at the level of a singular distal ulnar physis matching that of two physes of the radius.[36] Any disruption of either radial physis or, more commonly, the distal ulnar physis can lead to asynchronous growth of the radius and ulna.[9, 10] Resulting angulation can result in joint incongruity and uneven load distribution across the elbow and carpus, which in turn can cause secondary osteoarthritis and lameness.[37]

ALDs can arise from physeal trauma, malunion, congenital malformation, nutritional imbalances, and radiation exposure, among other causes leading to retardation of growth plates.[4, 9, 29, 38-42] Chondrodystrophic breeds, such as the basset hound, English bulldog, and dachshund, have been bred selectively for traits similar to disproportionate dwarfism in the human, which can result in conformational changes in the antebrachia that, in extreme cases, can result in severe angulation and malalignment.[36]

CORA Methodology

The *center of rotation of angulation* (CORA) methodology was first adapted from human medicine and applied to dogs in a 2006 study to provide a system of ALD classification and pre-operative planning utilizing a universal vocabulary that can be applied to any long bone deformity.[29] The CORA method relies on orthogonal radiographs prioritizing the positioning of the joints because the orientation of the joints is the starting point from which bone and limb alignment is determined.[43] Lines representing the orientation of the joints, or *joint orientation lines* (JOL) are drawn through predefined anatomic landmarks.[29, 44-47] Bone axes are then determined based on their intersecting angles with the JOLs utilizing referenced standards or the contralateral limb if unaffected. If more axes are elucidated than what should normally exist for the bone in question, the intersection(s) of the bone axes corresponds to the apex(es) of the deformity(ies) resulting in identification of a *center of rotation of angulation* (CORA). For example, the canine radius possesses a singular anatomic axis in the frontal plane.[29, 47] If a particular radius is examined utilizing the CORA methodology and determined to possess two anatomic axes in the frontal plane which intersect within the cortical confines of the bone, then the intersection of the axes would define a singular deformity or CORA and be considered a *uniapical* deformity (Fig 1).[48] Conversely, if the two axes do not intersect within the cortical confines of the bone, or do not intersect at all, additional axes must be determined and the deformity is classified as *multiapical*, or possessing more than a single CORA.[48] If two CORAs exist, this is referred to as a *biapical* deformity (Fig 2). For biapical deformities, the CORA planes can be described with respect to how their directions relate to one another. If the planes are oriented in the same direction, this represents a non-compensated deformity (a proximal radial varus paired with a distal radial varus for example), whereas CORAs with opposing planes indicate a partially compensated deformity (proximal varus compensated for by a distal valgus).[29] In this fashion, a system of nomenclature to classify deformities based on their direction, multiplicity, and the relationship to one another has been described.[29, 49]

CHAPTER 3: HYPOTHESES

The goal of this study was to retrospectively classify a group of ALDs in a population of dogs presenting to the University of Missouri Veterinary Medical Teaching Hospital with an associated lameness using the CORA methodology system of classification. We sought to examine the relationships between patient signalment, deformity classifications, and adjacent joint radiographic disease. We hypothesized that 1) antebrachial ALDs would be more complex (with respect to multiplicity) in chondrodystrophic dogs, and 2) more complex ALDs (those with > 1 CORA) would exhibit a higher incidence of concurrent joint radiographic disease in either the elbow or carpus.

CHAPTER 4: MATERIALS AND METHODS

Case Selection

Medical records from the database at the University of Missouri Veterinary Medical Teaching Hospital were searched from January 2006-December 2013 for canine patients with the diagnosis of "angular limb deformity." All patients with antebrachial, carpal, or elbow involvement were then selected from this group for further examination. Gender, reproductive status, age, weight, affected limb(s), and breed were recorded. Breeds of dog were categorized as either chondrodystrophic or non-chondrodystrophic. Those considered chondrodystrophic included dachshunds, shih tzus, English bulldogs, French bulldogs, beagles, basset hounds, Pembroke or Cardigan Welsh corgis, pugs, Lhasa apsos, and Maltese. Inclusion criteria included a complete medical record and either radiographs or computed tomographic (CT) analysis of the entire affected antebrachium. Specifically, radiographs had to be comprised of orthogonal views and include both the elbow and carpus. If torsion was present, a specific segmental radiographic technique[20, 30] must have been completed to allow the acquisition of joint-prioritized elbow/carpal-straight films in separate views. Cases which underwent analysis via CT and subsequent three-dimensional volumetric reconstruction were also included. If a patient presented multiple times for examination of progression, only the images taken at the first presentation were used for evaluation. Exclusion criteria included: incomplete medical record; incomplete or inappropriately positioned radiographs; ALDs arising from soft tissue laxity alone (suspected puppy hyperlaxity syndrome, carpal subluxation or luxation, and shoulder instability resulting in internal or external limb rotation). Similarly, cases with bony articular sources of angulation and malalignment, such as congenital radial head luxation and malformation of the carpal bones alone, were excluded as reliable joint orientation lines could not be identified for such intra-articular etiologies.

Deformity Classification

Images from all cases were reviewed by two authors, JK and DF. Objective data was averaged from the authors. If there were discrepancies between the authors in subjective findings (presence/absence of torsion or joint disease), the senior clinician's findings were used.[50] Deformities in the frontal plane were classified utilizing the previously described CORA methodology as it has been adapted for use in dogs.[29, 30] Briefly, joint orientation lines were determined for both elbow and carpus.[29, 30] The anatomic axis or axes of the radius was/were determined utilizing referenced normal joint orientation angles from both elbow and carpal joint orientation lines.[47] Despite many cases being only unilaterally affected and thus having a normal contralateral limb, for purposes of consistency, standard reference angles[47] were used to assess all cases in this study. All chondrodystrophic dogs, and any non-Labrador retriever dogs were assessed utilizing reference values previously established for non-Labrador retriever limbs (Table 1).[47] Values previously obtained from Labrador retriever limbs were used for all Labrador retriever dogs (Table 1).[47] Using this method, if more than one axis was defined in the frontal plane, the angular difference between the axes was measured and the point of intersection was considered a CORA. CORAs ≤ 3° were considered normal anatomic or radiographic variation from standard deviations based upon the 95% confidence intervals based on means of previously reported normal non-chondrodystrophic dogs.[47] The deformity classification was based on the number of CORAs present: uniapical (1 CORA); biapical (2 CORAs); or multiapical (> 2 CORAs). For biapical and multiapical deformities in the frontal plane, the direction of each CORA was recorded as either valgus or varus. If all CORAs possessed the same directionality, the deformity was labeled as *non-compensated*.[29] If the CORAs possessed opposing directionality the deformity was classified as being *partially compensated*.[29]

Sagittal plane analysis was completed, as previously described, and presence and magnitude of procurvatum or recurvatum recorded.[49, 51] Joint orientation lines were determined for both the elbow and carpus. The anatomic axes of the radius were determined utilizing reference joint orientation angles from sources as outlined above.[47] The angular intersection (θ) of the two segmental joint reference axes was measured. The total radial procurvatum was calculated as the sum of: the angular intersection between radial anatomic axes (θ); 90° minus the anatomic caudal proximal radial angle (aCdPRA); and 90° minus the anatomic caudal distal radial angle (aCdDRA) (Fig 3).[49, 51] Procurvatum was considered to be excessive if determined to be > 32° in Labrador retrievers and > 31° in non-Labrador dogs from previously reported normal ranges.[47] Relative recurvatum was considered to be present if determined to be < 21° in Labrador retrievers and < 20° in non-Labrador dogs from previously reported normal ranges.[47]

Antebrachial torsion was assessed based on clinical examination and imaging modalities and subjectively recorded as either present or absent, but not quantified. Torsion was considered as present if the elbow and carpus could not both be appropriately positioned and imaged in the same image (radiograph or CT). For example, if a true craniocaudal view of the elbow did not allow accurate craniocaudal positioning of the carpus.

Joint Disease

The presence of disease of either elbow or carpus was determined on radiographs and CT scans. Specific diagnoses affecting the elbow that were examined for included ununited anconeal process, fragmented medial aspect of the coronoid process, osteochondrosis, ununited medial humeral epicondyle, joint incongruity, and elbow osteoarthritis evidenced by the subjective presence of osteophytosis/enthesiophytosis and/or subchondral bone sclerosis. Abnormalities affecting the carpus included either palpable or radiographic carpal laxity and antebrachiocarpal osteoarthritis.

Statistical Analysis

Fisher's exact tests and χ^2 tests were used to determine statistical significance between categorical data.

Logistic regression analysis was performed to determine the association between the number of deformities in the frontal plane and chondrodystrophy. The number of deformities (the dependent variable) was coded dichotomously as i) one deformity and ii) two deformities. Independent variables included in the model were: age; weight; number of affected limbs (1 or 2); chondrodystrophic breed (yes/no); presence of excessive procurvatum (yes/no); presence of subjective torsion (yes/no); the interaction between age and weight; the interaction between chondrodystrophism and weight; and the interaction of the number of limbs affected with the presence of torsion. To determine the association between joint disease and the number of deformities in the frontal plane, additional logistic regression analyses were performed. Initially, the presence of any radiographic joint disease was investigated and coded dichotomously as i) any radiographic joint disease (within the elbow and/or carpus) and ii) no radiographic joint disease. Independent variables included in this model were: age; weight; number of affected limbs (1 or 2); chondrodystrophic breed (yes/no); the number of frontal plane deformities (1 or 2); presence of excessive procurvatum (yes/no); and presence of subjective torsion (yes/no). Additional logistic regression analyses were performed, specific to the joint affected. The presence of radiographic elbow disease and presence of radiographic carpal disease were separately modeled using the main effects from the combined joint disease model. All logistic regression assumptions were checked and met for analysis, with the exception of the independence of observations. Odds ratios and 95% confidence intervals were calculated for statistically significant data. A P-value of < 0.05 was considered statistically significant.

CHAPTER 5: RESULTS

Initially, 171 thoracic limbs from 117 dogs were identified. A total of 65 limbs from 46 dogs were excluded from 14 chondrodystrophic and 32 non-chondrodystrophic dogs due to: incomplete or inappropriately positioned radiographs (n = 55 limbs); congenital radial head luxation (n = 7); carpal luxation (n = 2); malformation of carpal bones (n = 1). A total of 106 thoracic limbs from 71 dogs met the inclusion criteria.

There were 26 spayed females (37%), 6 intact females (8%), 27 castrated males (38%), and 12 intact males (17%). The dogs ranged in age from 3 months to 69 months (mean = 15 months). The weight range was 2.4 kg to 54.4 kg (mean = 18.8 kg). Fifty-two left antebrachia and 54 right antebrachia were evaluated. Breeds included mixed breed (n = 16), basset hound (9), Labrador retriever (8), dachshund (6), Great Dane (4), shih tzu (3), German shepherd dog (3), Maltese (2), Dogue de Bordeaux (2), golden retriever (2), Rottweiler (2), Siberian husky (2), and one each of the following: Akita, border collie, Cardigan Welsh corgi, English bulldog, French bulldog, Irish wolfhound, Jack Russell terrier, Lhasa apso, mastiff, miniature poodle, pug, and standard poodle. Ninety-four limbs were evaluated with the use of digital radiographs, 6 with the use of digitized film-screen radiographs, and 6 with computed tomography.

There were 41 dogs, with 60 affected limbs, that presented at < 12 months of age and 30 dogs ≥ 12 months of age with 46 affected limbs that were evaluated. In the frontal plane, 21 (35%) limbs from patients that presented < 12 months of age were categorized with having a uniapical deformity, 38 (63%) as a partially compensated biapical deformity, and 1 (2%) as a multiapical deformity. For the patients that presented

≥ 12 months of age, their limbs were classified as uniapical in 14 (30%) and as a partially compensated biapical deformity in 32 (70%). Radiographic evidence of elbow disease was noted in 43 (72%) limbs from dogs < 12 months old and 35 (76%) limbs from dogs ≥ 12 months old. No association was noted in regards to age at presentation with severity of frontal plane deformity or radiographic elbow disease (P = 0.16 and 0.79, respectively).

There were 44 limbs from 26 chondrodystrophic dogs and 62 limbs from 45 non-chondrodystrophic dogs. In the frontal plane, 9 (20%) limbs from chondrodystrophic dogs were classified with having a uniapical deformity and 35 (80%) were classified with a partially compensated biapical deformity. Limbs from non-chondrodystrophic dogs were classified as: uniapical in 26 (42%); partially compensated biapical in 35 (56%); and multiapical in 1 (2%). With respect to CORA multiplicity, antebrachia of chondrodystrophic dogs were significantly associated with being biapically affected (P = 0.017) and 3 times more likely to have a biapical versus a uniapical deformity. Two limbs of chondrodystrophic dogs and 3 from non-chondrodystrophic dogs were excluded from sagittal plane calculations due to severe torsion, which prohibited an accurate measurement due to radiographic artifact. Of the 101 limbs evaluated in the sagittal plane, there was excessive procurvatum in 30 out of 42 (71%) chondrodystrophic limbs and 46 out of 59 (78%) non-chondrodystrophic limbs. No chondrodystrophic radius and ulna in this series demonstrated recurvatum. Five limbs (8.5%) from non-chondrodystrophic dogs showed relative recurvatum (less procurvatum than previously reported normal values). No association was noted between those dogs with sagittal (excessive procurvatum) and chondrodystrophism (P = 0.45). Some degree of torsional deformity was present in 33 (75%) chondrodystrophic limbs and 35 (56%) non-chondrodystrophic limbs. The incidence of subjective torsion in chondrodystrophic limbs was higher than in non-chondrodystrophic limbs (*P* = < 0.05, OR = 2.3).

Radiographic elbow disease was identified in 78 (74%) limbs and carpal disease in 29 (27%). More specifically, 38 (86%) antebrachia of chondrodystrophic dogs and 40 (65%) limbs of non-chondrodystrophic dogs had evidence of elbow disease. Chondrodystrophism was associated with the presence of elbow radiographic disease (*P* = 0.012) and resulted in 3.5 times higher likelihood of exhibiting one of the aforementioned conditions than non-chondrodystrophic dogs. This was not confirmed in a logistic regression model, when adjusting for other covariates (*P* = 0.12). Radiographic carpal disease was noted in 9 (20%) limbs of chondrodystrophic dogs and 20 (32%) limbs of non-chondrodystrophic dogs with no significant differences between the two groups (*P* = 0.87), when adjusting for covariates. Absence of radiographically or CT-based disease in both elbow and carpus was only noted in 19 limbs (18%).

A total of 35 uniapical and 70 partially compensated biapical deformities in the frontal plane were determined. No non-compensated biapical deformities were noted. There was 1 uniapical and 4 biapical deformities in which the degree of procurvatum could not be accurately calculated due to severe torsion. Biapical deformities (n = 56, 85%) were associated with excessive procurvatum more frequently than uniapical deformities (*P* = 0.003) and were 6.7 times more likely than uniapical deformities (n = 20, 59%) to have excessive procurvatum, when adjusting for other covariates. When evaluated, no associations were noted (*P* = 0.65) between biapical deformities with torsion (n = 48, 70%) and uniapical deformities with torsion (n = 18, 51%), when adjusting for other covariates.

Adjacent joint disease was noted in 25 (71%) uniapically affected limbs and 61 (87%) limbs with biapical deformities. Classification of a biapical deformity was significantly associated with the presence of adjacent joint disease ($P = 0.049$) and increased the odds 3.2 times over a uniapical deformity, when adjusting for other covariates. No significant association was noted in regards to adjacent joint disease with age, weight, being chondrodystrophic, excessive procurvatum, or torsion, when adjusting for other covariates. There were 19 (54%) limbs with uniapical CORAs, and 58 (83%) antebrachia with partially compensated biapical deformities with radiographic evidence of elbow disease. In dogs with a biapical deformity in the frontal plane, there was a significantly higher association ($P = 0.022$) of elbow radiographic disease than uniapical deformities, when adjusting for other covariates. The presence of two CORAs in the frontal plane increased the odds of identifying radiographic elbow disease by 3.6 times. Radiographic elbow disease was identified in 58 (85%) limbs with concurrent torsion present and in 20 (53%) limbs that did not have torsion. The presence of torsion had a higher incidence of radiographic elbow disease ($P = 0.005$). The odds of having radiographic elbow disease was 4.5 times higher in limbs that had torsion versus those without torsion noted, when adjusting for other covariates.

CHAPTER 6: DISCUSSION

Using the CORA methodology to study antebrachial ALDs, we were able to classify the deformities based on their frontal plane appearance while noting the presence or absence of excessive sagittal and transverse plane deformation. Our first hypothesis was partially accepted, as chondrodystrophic breeds were statistically more likely to present with complex deformities with respect to CORA multiplicity in the frontal and transverse planes. However, we were unable to demonstrate that chondrodystrophic breeds had more excessive angulation in the sagittal plane. The second hypothesis was also partly accepted as more severe frontal plane deformities had 3 times higher odds of having any joint radiographic disease and nearly 4 times higher odds of exhibiting some type of elbow disease specifically.

In the cases of antebrachial deformity presenting to this institution, a high percentage had concurrent radiographic or CT evidence of elbow disease (74%) at the time of initial presentation. Further, biapical deformities had concurrent elbow disease in 83% of our cases. Whereas older studies indicated a low incidence of concurrent elbow disease (12%), more recent literature has suggested a much higher occurrence of specifically lateral radial head subluxation in a subset of biapically affected dogs (93%).[8, 31] This occurrence of a relatively high percentage of elbow disease in our cases also appeared to be irrespective of the age of the dog and was equally documented in dogs both less than and greater than 12 months of age. Additionally, chondrodystrophic dogs were 3.5 times more likely to have a form of elbow disease than dogs of non-chondrodystrophic breeds. The role of concurrent elbow disease must be appreciated in dogs presenting with an antebrachial ALD as a potential source of pain, which may hinder post-operative prognosis, depending on the specific nature of the pathology and its severity. Unfortunately, it is often difficult to pre-operatively discern the relative importance of elbow pain from the mechanical dysfunction attributed to a highly angulated radius and ulna as sources of lameness in dogs presenting with antebrachial ALDs. A prospective study to monitor the progression of adjacent joint disease in ALD patients treated conservatively versus surgically would be helpful to understand the progression of joint disease and lameness over time.

It was noted that having > 1 deformity in the frontal plane was associated with excessive procurvatum in the sagittal plane. Thus, biapically affected antebrachia have a higher likelihood of being more severely affected in the sagittal plane as well, thus compounding their complexity and the potential difficulty when completing surgical corrections.

Chondrodystrophic dogs appear to more typically present with biapical deformities than uniapical deformities, and these deformities are almost always partially compensated with proximal radial varus in conjunction with distal radial valgus. The result is two complementary angulations resulting in medial translation of the antebrachium (Fig 2). The exact pathomechanics of how these changes develop is unknown. However, most chondrodystrophic dogs possess a natural angulated stance in the forelimbs to some degree, with elbows abducted and carpi medially translated. It is possible that this conformation becomes excessive and exaggerated in some dogs during development to a point where postural and ambulatory compensation is difficult and lameness ensues. The subsequent dysfunction may be mechanical from a large deviation of the overall limb's mechanical axis, or due to pathology of the elbow and/or carpus, or more likely, as a result of a combination of the two. What remains unknown is what, if any, initiating events cause such biapical angulation in affected dogs, and whether any interventional surgery could be employed to prevent its progression. Further, debate exists over the optimal way to treat such cases once skeletal maturity is reached; two osteotomies at the level of the CORAs,[729, 31] a single, mid-diaphyseal osteotomy to allow correction of the biapically-related translation,[34, 52] or simply addressing the elbow pathology alone. Additional research is required to substantiate existing treatment options.

Study Limitations

Several important limitations exist regarding this study including its retrospective nature, the predominant use of radiographs to classify the deformities, lack of torsional deformity quantification, and not determining the inter-observer variation on deformity classification. Most (94%) ALDs in this study were classified utilizing a segmental orthogonal radiographic technique as opposed to CT analysis.[20, 30] While segmental orthogonal radiography can be used to classify ALDs, miscalculations have been demonstrated in attempting to accurately quantify the magnitude of CORAs in situations of torsion-angulation in which the torsional component is > 15°.[20, 30, 33] To more accurately quantify the magnitudes of deformities in the frontal, sagittal, and transverse planes, CT studies with three-dimensional volumetric reconstruction is becoming a more desirable option for pre-surgical planning.[30, 53] In this study, calculation of the procurvatum in 5 limbs could not be achieved due to the presence of excessive torsion in which the only imaging modality obtained was radiography. The degree of angulation in the transverse plane (amount of torsion) was not quantified in our study due to the majority of cases only having plain radiographs. Thus torsional deformity was assessed in a subjective manner, which is a limitation to this study.

For purposes of consistency, a set of reference joint orientation angles were used to evaluate the affected limbs, regardless of whether the patient had a “normal” contralateral limb (Table 1). The authors of the present study routinely practice this method for all unilaterally affected chondrodystrophic dogs, as chondrodystrophy results in conformational changes even in “normal” dogs. Such changes are highly variable and could result in under-correction of the affected side if used as a template for normalcy, in the opinion of these authors. However, despite the advisable clinical practice of using the unaffected side of a unilaterally affected, non-chondrodystrophic patient, reference values were still used for all patients included here in an attempt to standardize the classification technique.

There is undoubtedly some variation between observers when quantifying CORA magnitudes. Whereas the purpose of this study was not to assess this variation, nor to determine specific ranges of deformity magnitudes, differences in their quantification could affect the resulting deformity classification. However, in related research, low intra- and interobserver variability among reviewers resulted from the measurement of the tibial plateau angle in dogs using digital radiographs and a method similar to what is reported here; deriving a joint orientation line and mechanical axis to calculate the resulting joint orientation angle.[54] Conversely, some studies indicate this variance to be as high as 13° in digitized films, which notably accounted for only 6% of our cases. [55] Additional research is needed to examine the intra- and inter-observer variation when specifically assessing antebrachia utilizing the CORA methodology with digital radiography and CT.

Another limitation of the current study was the lack of confirmation of joint disease with a more sensitive diagnostic methods in all cases. Other modalities such as MRI and arthroscopy have a higher sensitivity than radiographs for detection and grading of various joint pathology.[56-58] Thus, despite the high rate of concurrent joint radiographic disease noted in this study (82%), the actual incidence of joint pathology may have been underestimated.

Lastly, an additional limitation of this study lies with the exclusion criteria used. Angulation may arise from intra-articular malformations either as an isolated process or in conjunction with deformities of the radius and ulna. Because cases of antebrachial angulation whose deformity source was articular and existed within either the elbow or carpus were excluded, this cases series does not represent a comprehensive review of all sources of forelimb angulation distal to the humerus, but rather those only affecting the radius and ulna proper. The CORA methodology can still be used to help document and define intra-articular deformities, but frequently relies on the use of the overall limb evaluation, including the humerus and metacarpals, which would have eliminated the majority of cases presented here as those studies were not routinely performed. Thus we cannot comment on the nature, classification, or presentation of forelimb deformities that have occurred from intra-articular malformation.

Even with these limitations, this case series provides valuable categorical information on a large population of antebrachial ALDs for surgeons to use as a reference. Chondrodystrophic dogs were significantly more likely to have biapical radioulnar deformities than uniapical deformities and a higher incidence of elbow disease in comparison to non-chondrodystrophic breeds. More complex ALDs exhibited a higher incidence of concurrent joint disease, specifically with respect to the elbow. Biapical deformities are commonly seen in all types of dogs affected with antebrachial ALDs and elbow disease should not be underestimated as a potential contributing factor to their lameness.

FIGURES

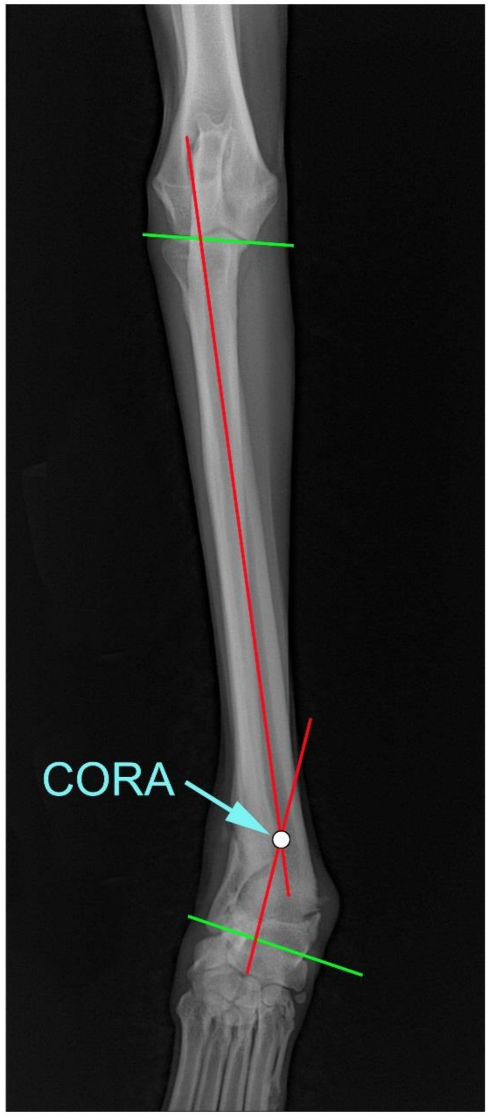

Figure 1. Example of a uniapical antebrachial deformity in a non-chondrodystrophic dog. Frontal plane carpal and elbow joint orientation lines (green) and radial anatomic axes (red) determined from published joint orientation angles. The single CORA is illustrated by the white circle.

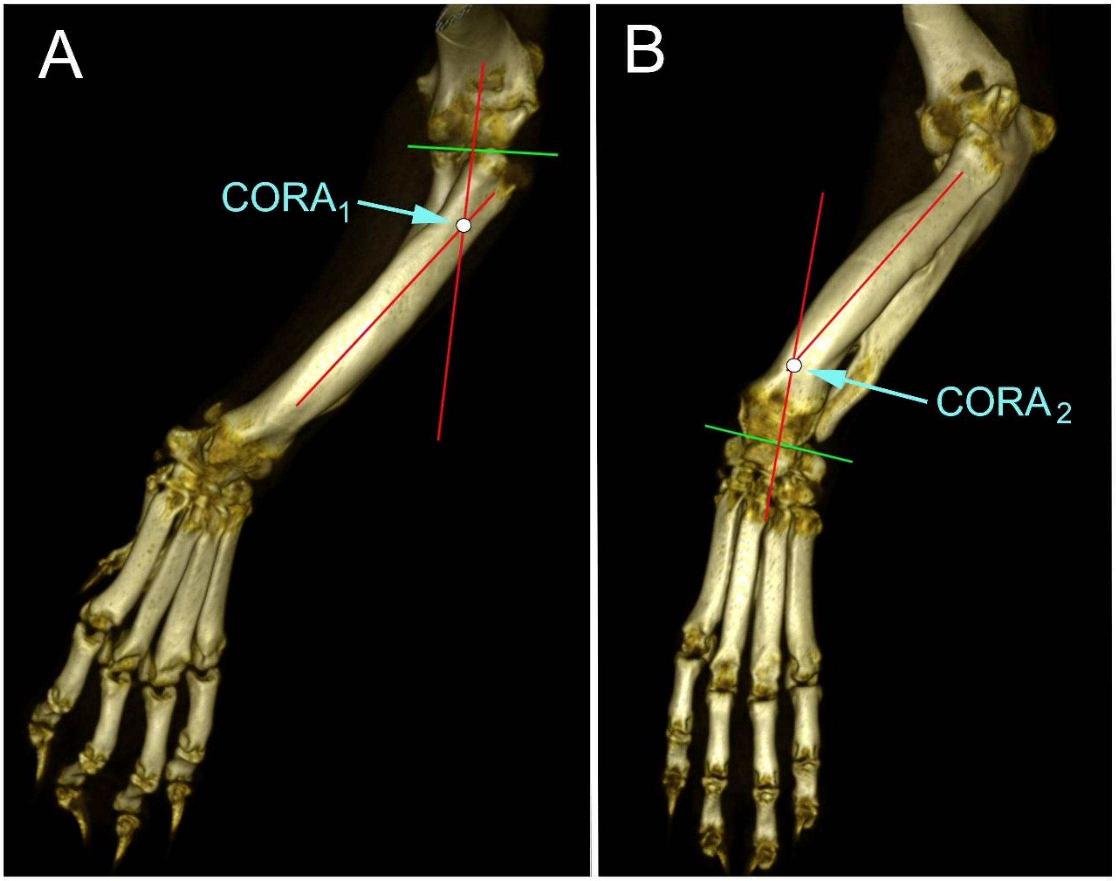

Figure 2. Example of a biapical, partially compensated antebrachial deformity with torsion in a chondrodystrophic dog as imaged by computed tomography and 3D volumetric reconstruction. (A) An elbow-straight view prioritizing craniocaudal imaging of the elbow and proximal radius. The green line denotes the elbow joint orientation line. The intersecting red line marks the proximal radial anatomic axis as determined by reference joint orientation angles for non-Labrador dogs. The second red line marks a best-fit anatomic axis for the remainder of the proximal radius. The intersection of the two axes in this view demonstrates the location of $CORA_1$. (B) A carpal-straight view prioritizing craniocaudal imaging of the carpus and distal radius. The green line denotes the radiocarpal joint orientation line. The intersecting red line marks the distal radial anatomic axis as determined by reference joint orientation angles for non-Labrador dogs. The second red line marks a best-fit anatomic axis for the remainder of the radius and is the same as in Fig 2A. The intersection of the two axes in this view demonstrates the location of $CORA_2$. Thus, this antebrachium possess a biapical partially compensated deformity with proximal varus and distal valgus.

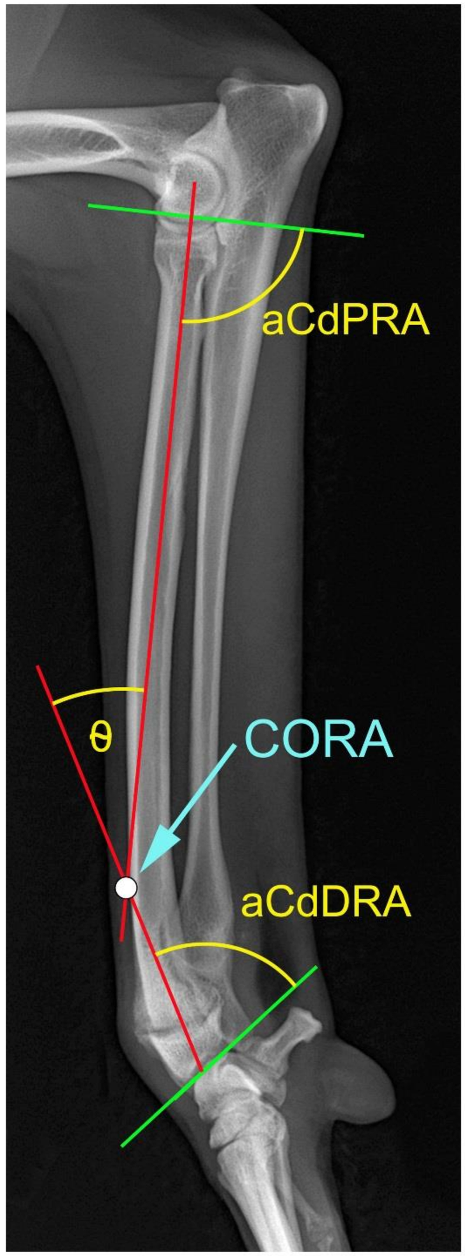

Figure 3. Example of how radial procurvatum is measured radiographically in the sagittal plane. Joint orientation lines (green) drawn on a sagittal radiograph along with radial anatomic axes (red) from previously published joint orientation angles (yellow). To calculate radial procurvatum: θ + (90° - aCdPRA) + (90° - aCdDRA): 30° + (90°-85°) + (90°-77°) = 48°, indicating excessive procurvatum.

TABLES

Table 1. Reference values used for frontal plane deformity classification. Mean values previously reported from 52 Labrador and 52 non-Labrador antebrachii.[47]

	aMPRA	aLDRA	aCdPRA	aCdDRA
Labradors	83°	86°	85°	77°
non-Labradors	81°	88°	88°	81°

aMPRA, anatomic medial proximal radial angle; *aLDRA*, anatomic lateral distal radial angle; *aCdPRA*, anatomic caudal proximal radial angle; *aCdDRA*, anatomic caudal distal radial angle.

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