Chapter 3

Prognostic Factors in Treating Antebrachial Growth Deformities with a Lengthening Procedure Using a Circular External Skeletal Fixation System in Dogs

L.F.H. Theyse[1], G. Voorhout[2], and H.A.W. Hazewinkel[1]

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[1] Department of Clinical Sciences of Companion Animals, Faculty of Veterinary Medicine, Utrecht University, Utrecht, The Netherlands
[2] Division of Diagnostic Imaging, Faculty of Veterinary Medicine, Utrecht University, Utrecht, The Netherlands

Abstract

The aim of this prospective clinical study was to evaluate the treatment of antebrachial growth deformities (AGD) with a lengthening procedure using a circular external skeletal fixation (CESF) system and to determine prognostic factors. The study included thirty-four dogs with unilateral AGD. Length deficits, angular and rotational deformities, elbow incongruity (EI), osteoarthritis (OA) of the elbow and carpal joint, function and cosmesis were determined before and after a CESF lengthening procedure. At presentation, EI (21/34 dogs; 62%), OA of the elbow joint (17/34 dogs; 50%), carpal OA (12/34 dogs; 35%) and concomitant elbow and carpal OA (5/34 dogs; 7%) were common findings. Treatment significantly improved function (normal in 20/34 dogs; 60%) and cosmesis (normal in 22/34 dogs; 65%). Angular and rotational deformities were almost completely corrected with small remaining length deficits. Elbow and carpal OA increased significantly during the follow-up period. Significant correlations were demonstrated between initial elbow OA and final function (R = 0.42, *P* = .02), initial function and final function (R = 0.41, *P* = 0.02), and initial ulnar and radial deficit and final cosmesis (R = 0.58, *P* = .0001 and R = 0.45, *P* = .008). Treatment of AGD with a CESF lengthening procedure was successful despite small remaining length deficits. Initial elbow OA, initial function, and ulnar and radial length deficits are prognostic factors in predicting the functional outcome of treatment of AGD with a CESF lengthening procedure in dogs.

Introduction

Antebrachial growth deformities (AGD) are the most common limb malformation in dogs.[23] Various causes for AGD have been described, including trauma of the antebrachial physes, chondrodystrophia, genetically induced deformities, metabolic disease and unbalanced nutrition.[11,16,28,38,46] Growth deformities are characterized by a combination of antebrachial length deficit, angular and rotational malalignment, elbow incongruity (EI), and carpal subluxation. The secondary effects may include osteoarthritis (OA) of the elbow and carpal joints. Further, EI has been associated with the occurrence of fragmented medial coronoid process (FCP) and ununited anconeal process (UAP).[31,49,50,51] Clinically, AGD will compromise limb function and cosmesis. The reduced function is characterized by lameness because of a combination of joint pain, decreased range of motion and antebrachial length deficit. The treatment of AGD is directed at correcting the complexity of malalignment, length deficit, and joint function and at preventing secondary degenerative changes.

The introduction of the concept of distraction osteogenesis, using circular external skeletal fixation (CESF), has revolutionized the treatment of AGD as lengthening procedures have now enabled the dynamic correction of length deficits.[1,20,21,36] In veterinary orthopedics, CESF has proven to be a highly dynamic system in treating length deficits, angular and rotational deformities, and EI.[26,32,41,48] Although several previous reports have described the use of CESF in dogs, these studies usually included a limited number of cases with AGD.[7,27,30,33] Our purpose was to evaluate the correction of AGD with CESF in a large group of dogs and to determine preoperative factors with a prognostic significance.

Material and Methods

Dogs

Thirty-four canine patients with unilateral AGD were evaluated prospectively during the period 1994-2002. The patient data included breed, age at treatment, gender, and body weight (BW). Functional and cosmetic grading of the affected limb was performed.[10,12] Limb function was graded by the degree of lameness: 0 = clinically normal, 1 = slight lameness, 2 = moderate lameness, 3 = marked lameness, intermittently non-weight-bearing, and 4 = continuous non-weight-bearing lameness. Limb cosmesis was graded by the severity of the deformity in comparison with the non-affected limb: 0 = no detectable deformity, 1 = minor alteration but difficult to detect, 2 = noticeable deviation from normal limb appearance, and 3 = severe changes from normal appearance. The minimum follow-up period after frame removal was 10 weeks.

Assessment of the antebrachial growth deformity

The rotational deformity of the antebrachium was assessed clinically by determining the planes of flexion and extension of the elbow and carpal joint and by measuring the angle between these planes with increments of 5°.[30] Radiographic examination of both antebrachia was performed preoperatively, immediately after surgery, immediately before and after removal of the CESF, and after a minimum follow-up period of 10 weeks. Final evaluation was always performed after closure of the proximal and distal physes of the radius and ulna in the contralateral antebrachium and termination of longitudinal growth.

Radiographs of the right and left antebrachium were made, including craniocaudal (CrCd) and mediolateral (ML) views centered on the elbow and carpal joints. The appearance of the antebrachial physes was assessed to determine the primary location of compromised longitudinal growth (Fig 1). Radiographs were also evaluated for the presence of a synostosis between the radius and ulna. Functional radial length was determined on the ML radiograph by measuring the distance from the center of the proximal radial joint surface (fovea capitis) to the center of the distal radial joint surface. Ulnar length was measured, using the same radiograph, from the proximal aspect of the olecranon to the end of the ulnar styloid process. Radial and ulnar length deficits were determined and expressed as a percentage of the longitudinal measurements of the non-affected side. The final extent of radial distraction was determined by measuring the width of the distraction gap and expressed as a percentage of the initial radial length. The overall increase in radial length after correction was determined and expressed as a percentage of the initial radial length.

Angular deformity was assessed in the ML and CrCd planes. The ML antebrachiocarpal joint angle was determined on the CrCd radiograph. The angle between a line drawn through the long-axis of the radius proximal to the deformity and a line parallel to the antebrachiocarpal joint was measured in increments of 5°. Carpal valgus was indicated with a positive grading and carpal varus with a negative grading. The CrCd antebrachiocarpal joint angle was determined on the ML radiograph. The angle between a line drawn through the center of the proximal and distal joint surfaces of the radius and a line parallel to the distal radial joint surface was measured in increments of 5°. Caudal subluxation of the carpus was indicated with positive grading and cranial carpal subluxation with a negative grading.

Fig 1. Antebrachial growth deformity with premature closure of the distal radial physis, resulting in a length deficit, incongruity of the elbow joint, and fragmentation of the medial coronoid process.

The median CrCd antebrachiocarpal joint angle in the non-affected limb was 15^o (range 10 – 20^o). Angular deformities were determined by comparing the measurements of the affected side with the normal contralateral limb angles.

ML and CrCd radiographs of the elbow joint were taken and evaluated for the presence of EI, FCP, UAP, and OA. Incongruity of the elbow was determined on the ML radiograph, using a template with circles of increasing diameter to match the trochlear notch of the ulna and radial head, respectively. The position of the circles was delineated on the radiograph and the difference in overlap between both circles was measured (mm) and corrected for the magnification factor to establish the size of the step-defect (Fig 2).

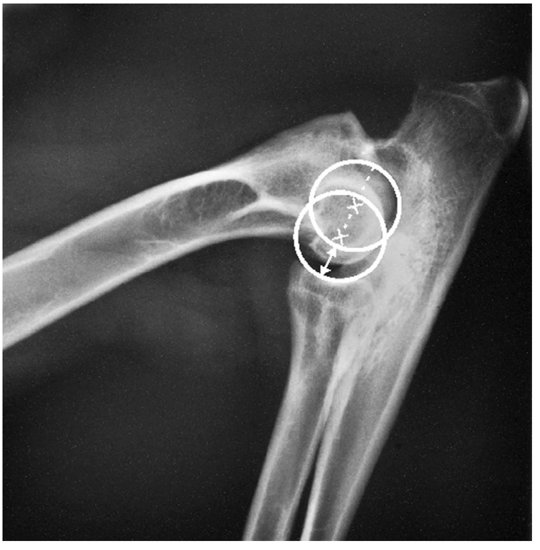

Fig 2 Mediolateral radiograph of the elbow joint with superposed templates to determine the amount of elbow incongruity (same dog as in Fig 1).

Incongruity because of a radial length deficit was given a negative mark and EI due to an ulnar length deficit a positive mark. Elbow OA was graded from 0 to 3 according to the guidelines of the International Elbow Working Group (IEWG). In this system grade 0 typifies no OA, grade 1 osteophytes < 2mm, grade 2 osteophytes between 2-5mm, and grade 3 osteophytes > 5mm at well-defined locations.[15] Carpal OA was graded in a similar way by measuring the size of the osteophytes on the cranial, caudal, lateral and medial aspect of the antebrachiocarpal joint.

Frame design

The CESF was assembled using the Polyfix® system (Polyfix, Grenoble, France) supplemented with IMEX™ parts (IMEX Veterinary Inc., Longview, TX, USA). The system included aluminum full, three-quarter, and half rings with diameters ranging from 60 to 110 mm, stainless steel connecting bars with a 6 mm diameter and a 1 mm pitch, stainless steel connecting bolts and nuts, hinges and angular motors. Depending on the size of the dog transosseus wires ranged from 1.2 to 1.6 mm in diameter. No stopper or olive wires were used in these dogs. The basic CESF frame design included a proximal and distal full ring adjacent to the radial osteotomy and secured to the radius with 2 tensioned transosseus wires per ring and a proximal three-quarter ring secured to the radius with 1 tensioned transosseus wire. Tension was applied with a dynamometric wire tensioner (Hofmann SaS, Monza, Italy) with an equivalent of 20 kg in dogs with a BW up to 10 kg, an equivalent of 40 kg in dogs with a BW between 10 and 20 kg, an equivalent of 60 kg in dogs with a BW between 20 and 30 kg, and an equivalent of 80 kg in dogs with a BW between 30 and 40 kg. To reduce EI dynamically an extension or flag was incorporated into the frame design. This flag consisted of two treaded rods with one or two partial rings, which were attached to the proximal ulna with one or two tensioned transosseus wires. For additional stability, a supplemental proximal ring on the radius was used in selected cases (Fig 3). Care was taken to allow free motion in flexion of the elbow joint, which was accomplished by applying a partial radial ring when necessary. In two large and heavy dogs (BW > 38 kg), a 2nd distal radial ring was placed to enhance frame stability.

Fig 3. Circular external fixation system during the lengthening procedure with flag on the ulna to correct the incongruity of the elbow joint. The frame includes a proximal and distal full ring on the radius adjacent to the distraction zone, a three-quarter ring on the proximal radius for additional stability, and a flag with a half ring mounted on the proximal ulna (same dog as in Fig 1).

Surgical treatment

Correction of the deformity included rotational correction, angular correction, dynamic reduction of the elbow joint incongruity, and antebrachial lengthening, based on the preoperative data. The procedure was started with the partial ulnectomy in the distal third of the ulna without the use of a fat graft. In dogs diagnosed with a FCP, a medial arthrotomy of the elbow joint was performed, the medial and lateral coronoid process was examined, and fragments were removed. After placing the proximal ring without attaching is to the bone, the distal ring was secured, using two transosseus wires, perpendicular to the longitudinal axis of the distal radius. The position of the distal radial ring was determined based on the radiographic angular deformities in the ML and CrCd planes. When applicable a second distal ring was placed parallel to and at a distance of 4 cm of the first ring.

Correction of the rotational deformity was planned and performed as a 1-stage procedure in all cases. Correction of the angular deformity was performed as a 1-stage procedure, using a closing wedge osteotomy, in the first 24 cases. Dynamic correction with a hinge and angular motor configuration was available from case 25 onward. The hinge and angular motor configuration was used depending on the size of the patient and severity of the angular deformity. The location of the hinges and angular motor were determined as described.[33] Osteotomy of the radius was performed as close as possible to the center of the deformity through a medial approach using an oscillating saw and ample lavage. The periosteum was preserved, while minimizing trauma to the soft tissues. The frame was secured to the proximal radius with 2 transosseus wires on the full ring and 1 transosseus wire on the three-quarter ring. If EI had to be addressed, a flag on the ulna was incorporated into the frame design.

Postoperative care consisted of analgesics (buprenorphine, 10µg/kg 4 times daily subcutaneously) for 3 days, a full-leg bandage for the first 3 days, and a protective bandage incorporating the CESF only, thereafter. Exercise was restricted to leash walks for the duration of the treatment.

Correction of the EI was performed by either raising or lowering the ulnar flag at a rate of 0.5 mm twice daily, and was started the day after surgery. The measured amount of EI, corrected for the radiographic magnification factor, was restored and the result was evaluated on the ML radiograph of the elbow joint using the template, immediately after the expected reduction of the step-defect (Fig 4 and 5). After a latency period of 3 days, the lengthening procedure was executed by distracting the radius at a rate of 0.5 mm twice daily. The distraction rate of the angular motor was adjusted to match an elongation of 1 mm a day at the opening side of the osteotomy. Distraction was verified radiographically on a weekly basis until the determined amount of lengthening was accomplished. Dogs were discharged after correction of EI and the remainder of the radial distraction was performed by the owners. The distraction of the antebrachium was stopped when the length deficit was corrected or when the carpal joint showed early signs of carpal flexor contracture with the inability to extend the joint.

After lengthening was stopped, consolidation of the distraction zone was evaluated every 2 weeks until the bone was judged strong enough to allow for frame removal. The duration of treatment from CESF placement to frame removal was determined. The occurrence of complications concerning the CESF, transosseus bone wires, or soft tissues were recorded. After consolidation of the distraction zone, the frame and transosseus wires were removed under sedation and a protective bandage was applied for 2 days. Exercise was limited to leash walks for at least another 2 weeks. The result of the lengthening procedure was evaluated by measuring the length of the distraction zone, using the radiographs taken immediately after frame removal. The final results of the correction of the AGD and the lengthening procedure were evaluated when longitudinal growth in the non-affected leg had ceased by measuring radial and ulnar length, joint angles, EI and elbow and carpal OA as described earlier. At final follow-up, function and cosmesis were graded.

Fig 4. Mediolateral elbow radiograph centered on the joint after correction of the elbow incongruity (same dog as in Fig 1).

Fig 5. Result of lengthening procedure and correction of elbow incongruity at 4 months postoperative (same dog as in Fig 1). The distraction zone is still distinguishable despite advanced remodeling. There is minimal osteoarthritis (OA) in the elbow joint and no OA in the carpal joint.

Evaluation of prognostic factors

To identify factors, which could predict the outcome of treatment of AGD with a CESF, correlations between initial function and cosmesis, age, rotational, CrCd, and ML angular deformities, radial and ulnar length deficits, EI, FCP, initial OA of the elbow and carpal joints, and function, cosmesis, and OA at the end of the follow-up period were assessed. Correlations between final function, final elbow and carpal OA, final radial and ulnar deficits, remaining angular deformities and EI, radial distraction, overall lengthening, duration of treatment and follow-up were also determined.

Statistical analysis

Preoperative radial and ulnar deficits, ML, CrCd, and rotational angles, EI, OA grade of the elbow and carpal joints, cosmesis and function were compared with the results of these parameters after treatment, using a Wilcoxon sign rank test. Correlations between the non-parametric data were determined using a Spearman test. The effect of elbow OA on function was corrected for the influence of carpal OA and vice versa. All statistical analyses were performed, using computer software (SPSS 10.1, SPSS Inc., Chicago, IL, USA). A *P*-value < .05 was considered significant. Results were reported as mean ± SD.

Results

The study included 32 dogs with normal skeletal proportions except for the AGD and 2 chondrodystrophic dogs, both Basset Hounds. Labrador (n = 6, 18%) and Golden retriever (n = 4, 12%) dogs were the most common breeds. On admission, the mean age of the dogs was 7 months (range, 3 - 19 months) with 24 dogs (70%) < 7 months of age and 10 dogs (30%) > 8 months. The mean weight was 21 kg (range, 6 - 40 kg). Gender distribution was 15 females (44%) and 19 males (56%). Function was impaired in all dogs and cosmesis was graded abnormal in all but one. Initial function was scored as grade 1 lameness in one dog, grade 2 lameness in 27 dogs (79%), and grade 3 lameness in 6 dogs (18%). Initial cosmesis was scored as no deformity in one dog, grade 1 deformity in 6 dogs (18%), grade 2 deformity in 15 dogs (44%), and grade 3 deformity in 12 dogs (35%). Rotational deformity was present in 15 dogs (44%).

All dogs demonstrated a combined growth disturbance with involvement of both the distal radial and ulnar growth plates, resulting in radial and ulnar length deficits. In 20 dogs (59%), the distal radial physis was the most affected growth plate, while the distal ulnar physis was affected primarily in 13 dogs (38%). In one dog, the proximal radial physis was the most affected growth plate. In all cases, the onset of the AGD could be contributed to a traumatic event. Synostosis was present in 5 dogs (15%). Angular deformity in the ML and CrCd plane was present in 33 dogs (97%). ML angular deformity was found in 27 dogs (79%) with carpal valgus in 23 and carpal varus in 4 of these dogs (85% and 15%, respectively). Valgus deformity could be attributed primarily to the distal ulnar physis in 12 dogs (52%) and to the distal radial physis in 11 dogs (48%).

CrCd angular deformity was present in 30 dogs (88%) and caudal carpal subluxation in 23 dogs and with cranial carpal subluxation in 7 dogs (77% and 23%, respectively). Caudal subluxation of the carpus could be attributed to the distal ulnar physes in 11 of 13 dogs (85%) and to the radial physes in 12 of 21 dogs (57%). Cranial subluxation of the carpus was demonstrated in 6 of 21 dogs (29%) with radial length deficits. External rotation of the radius was found in 11 of 13 dogs (85%) primarily with growth arrest of the distal ulnar physis, whereas only 4 of 21 dogs (20%) had external rotation from a primarily radial length deficit.

EI was demonstrated in 21 dogs (62%) with AGD and was caused by radial length deficits in 17 (81%) and by ulnar length deficits in 4 dogs (19%). A combination of EI and synostosis was present in 2 dogs (6%). The measurements of radial and ulnar deficits, angular and rotational deformities, and EI are presented in Table 1.

Table 1. Radial and ulnar length deficits, angular and rotational deformities, and elbow incongruity (EI) in 34 dogs with unilateral antebrachial growth deformities (AGD) before surgical correction.

AGD	Range	Median	Mean ± SD
Radial deficit (%)	2 - 25	13.4	12.8 ± 5.5
Ulnar deficit (%)	1 - 19	7.9	8.5 ± 4.5
ML angle (^{o})	-40 - 50	20	15.4 ± 21.8
CrCd angle (^{o})	-30 - 50	10	12.2 ± 17.9
Rotational angle (^{o})	0 - 80	0	17.2 ± 23.3
EI (mm)	- 10 - +7	-1	- 0.4 ± 4.5

ML angle is the angulation of the antebrachiocarpal joint in the mediolateral (ML) plane with negative values indicating carpal varus and positive values indicating carpal valgus.
CrCd angle is the angulation in the antebrachiocarpal joint in the craniocaudal (CrCd) plane with negative values indicating cranial carpal subluxation and positive values indicating caudal carpal subluxation.
EI is presented with negative values to indicate a radial length deficit and with positive values to indicate an ulnar length deficit.

Fragmentation of the coronoid process was diagnosed radiographically in 9 dogs (27%), and was always found in combination with EI caused by a radial length deficit. The breed distribution of FCP was 3 Bernese Mountain dogs, 2 Labrador Retrievers, a miniature Schnauzer, a Beagle and 2 small mongrel dogs.

UAP was not found in this patient group. OA of the elbow joint occurred in 17 dogs (50%) and was found concurrently with EI in 16 of 21 dogs (76%). Initial elbow OA was scored as grade 1 osteophyte formation in 15 dogs (44%), and grade 2 osteophyte formation in 2 dogs (6%). Carpal OA occurred in 12 dogs (35%), and all of these dogs had grade 1 osteophyte formation. In 5 dogs, concurrent OA of the elbow and carpal joint was present (5/34; 14%).

Treatment of AGD, using the basic CESF frame design with a closing wedge osteotomy in 30 dogs (88%) and a hinge-and-motor CESF with dynamic correction of the angular deformity in the remaining 4 dogs (12%), was uneventful. A lengthening procedure was performed in all dogs. After completing dynamic distraction, the consolidation of the bone regenerate progressed without serious complications. No differences were found between dogs treated with the closing wedge technique or the hinge-and-motor CESF for any of the variables investigated. Treatment duration was 6.3 ± 1.5 weeks, with a follow-up period of 17 ± 12 weeks. The most common complication was wire tract infection, which occurred in 20 dogs (59%). Wire tract infections were almost completely limited to the bone wires of the flag on the proximal ulna and usually started in the 3rd week after surgery. Breakage of transosseus wires occurred in 2 dogs (6%), and included the wires mounted on the distal radial ring. In both dogs, the CESF was caught on an object and when the dog struggled to break free, the transosseus wires were damaged. Immediate replacement of the transosseus wires was sufficient to re-establish CESF stability.

After treatment, function and cosmesis had improved significantly. Function was determined to be normal in 20 dogs (60%), while 14 dogs (40%) had grade 1 lameness. Lameness could be attributed to the elbow joint in 5 dogs (35%), to the carpal joint in 2 dogs (15%) and to a combination of the elbow and carpal joints in 7 dogs (50%). An FCP had been removed in 5 dogs with elbow joint lameness (60%). Cosmesis was restored in 22 dogs (65%), while 12 dogs (35%) had grade 1 deformity and 7 of these dogs (58%) had carpal valgus despite correction of the angles of ML deformity, indicative of malformation within the carpus.

Radial and ulnar deficits, angular and rotational deformities, and EI improved significantly after treatment (Table 2). Radial distraction was 12 ± 7 mm (range, 2 - 26 mm) corresponding to 11 ± 7% (range, 1 - 27%) of the initial radial length. The result of the lengthening procedure was 15 ± 9 mm (range, 2 - 39 mm), corresponding to 13 ± 10% (range, 1 - 40%) of initial radial length. Radial and ulnar length deficits were corrected completely in 4 dogs (12%) and 5 dogs (15%), respectively, whereas minor deficits were present in the remaining dogs (88% and 85%, respectively). ML and CrCd angular and rotational deformities were restored in 27 dogs (79%), 22 dogs (65%) and 32 dogs (94%), respectively. EI was corrected in 20 of 21 dogs (95%). Final function was graded as clinically normal in 11 of these dogs (52%).

Radiographic diagnosis of FCP was confirmed during arthrotomy in 9 dogs, and the FCP was removed. In 7 of these dogs, fragmentation involved both medial and lateral coronoid processes. At final follow-up, OA of the elbow and carpal joint was found in 20 dogs (58%) and 19 dogs (56%), respectively, with a significant increase in comparison with preoperative OA scores. Concurrent OA of the elbow and carpal joint was present in 11 dogs (32%). Final elbow OA was scored as grade 1 osteophyte formation in 14 dogs (41%) and grade 2 osteophyte formation in 6 dogs (18%). In the dogs with EI, only 5 of 21 (24%) were considered free of OA at follow-up. None of these dogs was diagnosed with FCP and the median age of these dogs was 6 months (range, 4-6 months). Final carpal OA was scored as grade 1 osteophyte formation in all 19 dogs.

Table 2. Radial and ulnar length deficits, angular and rotational deformities, and elbow incongruity (EI) in 34 dogs with unilateral antebrachial growth deformities (AGD) after surgical correction, using a lengthening procedure with a circular external skeletal fixation (CESF) system.

AGD	Range	Median	Mean ± SD
Radial deficit (%)	-1 - 16	6.7	7.1 ± 5.1*
Ulnar deficit (%)	-9 - 14	4.6	4.8 ± 4.6*
ML angle (^{o})	0 - 10	0	2.1 ± 3.9*
CrCd angle (^{o})	-10 - 15	0	-0.1 ± 5.6*
Rotational angle (^{o})	0 - 20	0	1.2 ± 4.8*
EI (mm)	-1 - 0	0	-0.1 ± 0.2*

ML angle is the angulation of the antebrachiocarpal joint in the mediolateral (ML) plane with negative values indicating carpal varus and positive values indicating carpal valgus.
CrCd angle is the angulation in the antebrachiocarpal joint in the craniocaudal (CrCd) plane with negative values indicating cranial carpal subluxation and positive values indicating caudal carpal subluxation.
EI is presented with negative values indicating a radial length deficit and positive values indicating an ulnar length deficit.
* Significant improvement in comparison with these values before correction of the AGD (Table 1) ($P < .001$).

Significant positive correlations were demonstrated between initial elbow OA and final function ($R = 0.42$, $P = .02$) and between initial function and final function ($R = 0.41$, $P = .02$). In other words, a higher initial OA grade resulted in a higher final function grade and thus more severe lameness. By analogy, a higher initial function grade resulted in more severe lameness at final follow-up. Initial ulnar and radial deficits (R = 0.58, *P* = .0001 and R = 0.45, *P* = .008, respectively) and final ulnar and radial deficits (R = 0.51, *P* = .002 and R = 0.35, *P* = .04, respectively) were positively correlated with final cosmesis. In addition, initial EI (R = 0.49, *P* = .003) and FCP (R = 0.48, *P* = .004) showed a positive correlation with final elbow OA. Initial EI was positively correlated with the presence of an FCP (R = 0.57, *P* = .0001). Final elbow OA was more severe with increasing age on admission (R = 0.37, *P* = .03) In other words, treatment at a later age resulted in more severe elbow OA at follow-up. Increasing degrees of ML angular deformity resulted in more severe final carpal OA (R = 0.34, *P* = .04). A negative correlation was found between the ML and CrCd angular deformity and final elbow OA (R = -0.42, *P* = .01 and R = -0.37, *P* = .03, respectively), indicating that more severe initial carpal angular deformity resulted in less OA in the elbow joint. No significant correlation was found between initial EI and final function. Final function correlated positively with final elbow OA (R = 0.51, *P* = .002) and final cosmesis (R = 0.38, *P* = .02), but not final carpal OA. Final carpal OA was positively correlated with both the amount of radial distraction and overall lengthening (R = 0.45, *P* = .008 and R = 0.38, *P* = .02, respectively).

Discussion

AGDs vary considerably in the extent of malformation, which contributes to a heterogeneous patient group. The common factor in our study was that all dogs had unilateral AGD caused by a traumatic event. On admission, 70% of the dogs were < 7 months of age. Cessation of radial growth usually occurs between 8 and 9 months of age, which implies functional growth plates and thus growth potential in the contralateral antebrachium of these dogs with AGD.[5] Assessment of growth potential in the affected limb is essential during the planning of correction of length deficits. Unfortunately, there is no accurate way to predict the amount of remaining growth of the antebrachium during and after treatment, and close radiographic monitoring of longitudinal growth is the best option.[40] Another problem is unequal growth within the physis, which can result in relapse deformity of the limb after correction. These general considerations would favor treatment of the patients at an age when length growth has ceased, but this would discount the deleterious effects of growth deformities on joint function and the development of OA. Normal joint function can only be achieved by realignment of the mechanical axis of joint movement and reducing EI and carpal subluxation as soon as possible. In our study, OA was already present in these dogs on admission and proved to be a major factor in outcome.

Gender distribution slightly favored male dogs, which, in combination with behavioral aspects, may indicate that higher growth rates render the physes more susceptible to traumatic disturbance. As function and cosmesis were clearly comprised and most dogs still had significant growth potential, correction of the AGD with a CESF lengthening procedure was indicated.

Synostosis of the radius and ulna usually is a consequence of high-impact antebrachial fractures and has been described in young dogs as a contributing factor in the development of AGD.[25] The incidence of synostosis of 15% in our study was considerable and is of importance as removal of the synostosis is critical when restoring antebrachial alignment and in correcting EI and carpal subluxation. Furthermore, synostosis will restrict pronation and supination of the antebrachium and thus compromise function.

In the antebrachium, the distal growth plate of the ulna by its configuration and subsequent high growth rate is reported to be more vulnerable to trauma than the radial physes.[38] This will typically result in radius curvus syndrome with cranial bowing of the radius, exorotation of the antebrachium, and valgus of the carpus. In the clinical situation, isolated disturbance of just 1 physis is not a common finding and usually both the distal radial and distal ulnar growth plates will be affected. The degree of growth disturbance within the radial and ulnar physes will vary from patient to patient, resulting in a heterogeneous presentation of AGD.

We demonstrated a higher prevalence radial physeal growth disturbance, which may be attributed to the fact that we not only looked at the radiographic appearance of the physes but also measured the effect of growth disturbance on radial and ulnar length. Although the radial longitudinal growth deficit was more substantial than the ulnar growth deficit, the overall result was valgus deformity in most dogs, which is consistent with other reports.[10,38] This observation suggests that trauma to the distal radial physis in most cases elicits an asymmetrical growth arrest, which is more severe on the lateral side of the physis.[17,39,46] Carpal varus was not a common finding Compromised longitudinal growth of the distal radius may results in cranial subluxation of the carpus as we found. In contrast, compromised growth in the distal ulnar physis can cause caudal subluxation of the carpus. Internal rotation of the antebrachium was not encountered, and external rotation was typically found in conjunction with primarily ulnar length deficits.

EI in conjunction with AGDs has been reported in several studies.[25,26,27,31] Radiographic evaluation of in vitro-created EI was associated with relatively poor sensitivity and specificity.[34] However, EI in pathological cases is characterized by malformation of the humeroulnar, humeroradial, and radioulnar joint surfaces with subsequent OA. In our study, the high prevalence of EI was critical for both initial lameness and elbow OA after treatment. A major problem in evaluating EI is the lack of a uniform grading system. The grading system that we used was effective in expressing the severity of EI. It is clear that this method is an oversimplification of EI and only focuses on the step defect between radius and ulna in the elbow joint. Malformation of the elbow joint cannot be assessed with this radiographic technique. In our opinion, the AP radiograph of the elbow joint was not useful for evaluation of EI as the step defect is obscured in this projection.[34] Nevertheless, our method proved to be helpful in determining the amount of correction required to restore congruity and to assess the result of treatment.

The correlation between EI and FCP seems to support the hypothesis that an abnormal weight distribution on the ulna is a pathogenic factor for FCP.[22,49] In small breed dogs, the occurrence of a FCP is a rare finding, but FCP coincided with EI in 4 small dogs in our study. The fact that fragmentation of the lateral coronoid process was also found frequently is consistent with this concept of overloading of the ulnar joint surface. As FCP, especially in young dogs, can be difficult to diagnose radiographically, an underestimation of the concurrence of FCP with EI in dogs with AGD is to be expected.[15] In contrast, FCP with or without EI is a regular finding in Bernese Mountain dogs and Labrador Retrievers as part of elbow dysplasia. Ubbink showed that FCP and EI have a genetic basis in Bernese Mountain dogs, but are distinct entities, which nuances the former hypothesis of overloading.[45] Critical evaluation of both EI and FCP is essential, as both were shown to cause progressive elbow OA. Three-dimensional imaging techniques are invaluable in assessing EI, but need further study.

Angular deformities of the antebrachium will lead to abnormal loading of the carpal joint and subsequent OA. Although most dogs presented with a combination of valgus or varus with cranial or caudal carpal subluxation, OA in the carpal joint was not as common as in the elbow. A possible explanation for this finding might be that the dog compensates for the angular deformity by altering foot placement and thus to some extend normalizes joint loading. Compensation for the EI cannot be achieved in this respect. Although the importance of deviation of the carpal joint axis is recognized in literature, very little is reported on the impact of this problem on carpal development, function, and secondary OA.[4,10,35] Literature concerning the treatment of AGD, focuses on the correction of the ML and CrCd carpal joint angles, but does not address the occurrence of carpal deformity.[26,27,32,33,37] Malformation of the carpal bones during growth can lead to angular deformity within the joint, which is not susceptible to correction (Fig 6). In our study, carpal malformation was judged responsible for carpal valgus, which occurred despite proper realignment of the distal antebrachial joint surface.

By analogy with EI, there is no grading system to classify carpal malformation. We have focused on the secondary carpal OA resulting from abnormal joint loading and carpal malformation. The high prevalence of carpal OA that we found has not been reported previously, but is in accordance with loss of carpal range of motion reported previously.[27,33]

Restoration of the functional alignment of the elbow and carpal joints is critical in treating AGD. Although dynamic correction of rotational deformities is possible, this requires an elaborate frame design and the character, and the character and nature of dogs do not make this a feasible option.[19,47] In view of this, we performed correction of rotational deformity acutely during surgery. Correction of angular deformities and limb lengthening were executed successfully, using a closing wedge technique or dynamic correction with the hinge and motor configuration. The closing wedge correction of the angular and rotational deformities had the advantage of direct visualization of joint alignment. Further, the closing wedge osteotomy allowed for a large area of contact between the proximal and distal parts of the radius. This is advantageous for revascularization of the osteotomy zone before distraction. In an open wedge osteotomy with limited bone-to-bone contact, revascularization of the distraction zone will take longer requiring an extended latency period. A disadvantage of the closing wedge technique was the initial bone loss, which had to be compensated for during distraction.

Fig 6. Malformation of the carpal bones, resulting in valgus deformity within the carpus. The mediolateral angle of the antebrachiocarpal joint is near normal. This type of malformation is not amenable to angular correction of the antebrachium.

Although the hinge and motor configuration had the advantage of dynamic correction of the angular deformity, its size restricted its use in smaller dogs. Another problem, especially in caudal subluxation of the carpus, was assessing the ability of the antebrachial flexor tendons and muscles to adapt to the strain put on these structures during dynamic correction of the deformity. The major concern was relative flexor tendon contracture, occurring before realignment of the antebrachiocarpal joint was accomplished, leading to carpal flexion, abnormal weight bearing, and possibly joint damage. In an experimental study in dogs involving femoral lengthening, cartilage fibrillation and even necrosis in the stifle joint was reported.[42] Compression of the joint because of the distraction was held responsible for this finding as the combination of simultaneous lengthening and joint distraction was able to prevent this consequence.[9,43] Managing established carpal flexor contracture can be very frustrating and prevention is critical.[18] Acute correction of the antebrachiocarpal joint angles should be considered in treating severe caudal carpal subluxation with a restricted ability to extent the carpus.

Although Frierson reported an adverse effect of using an oscillating saw on bone regeneration in a canine tibial lengthening model, this observation is contrary to other experimental studies.[6,13,24] We used an oscillating saw in combination with adequate cooling by lavage, and it seemingly did not have an adverse effect on osteogenesis as the duration of treatment and the frequency percentage of complications were similar to other reports.[7,26,27,32,33] Osteogenesis and consolidation progressed rapidly in these dogs, which is assumed to be related to their young age, metaphyseal osteotomies, and increased blood flow during distraction.[2,3]

Most wire tract infections were encountered at the site of the ulnar flag. The ulnar flag restricts normal supination and pronation of the antebrachium, which may cause irritation and infection of soft tissues and subsequent loosening of the ulnar transosseus wires. A flag design, allowing free pronation and supination, might overcome this problem.[39] Breakage of transosseus wires was always associated with external trauma to the CESF, but proper care should prevent this complication. In larger and heavier dogs, the frame design should preferably incorporate a 4-ring construct with 2 tensioned bone wires/ring. In view of the distal location of most AGDs and the small size of distal radial segment, we typically used a frame with a single distal radial ring. This frame design had no distinguishable adverse effect on the incidence of complications.[29]

The major disadvantage of traditional external fixators and bone plates in comparison with CESF is the inability of these methods to correct antebrachial length deficits and EI dynamically.[4,10,12,35,37] Nevertheless, angular deformities have been corrected successfully using these methods with comparable results of angular realignment as we found.[4] The results of the lengthening procedure and the correction of the angular and rotational deformities were in accordance with previous reports on the treatment of AGD with CESF.[7,25,26,27,32,33] The limiting factor of the lengthening procedure was the inability of the flexor tendons and muscles to keep up with the distraction rate. Although physiotherapy and supporting bandages may promote extension of the carpal joint, imminent flexor contracture necessitated the end of distraction before complete correction of the length deficit was accomplished.[8]

The distinction between the amount of active radial distraction and the result of the lengthening procedure was made for the following reasons. Firstly, correction of angular and rotational deformities in itself can result in an increase of the functional length measured. Secondly, the growth potential of still active radial physes can contribute to the overall result of lengthening. The result of the correction of AGD will depend on the combination of realignment, active distraction, and growth potential of the antebrachium. The remaining length deficits had a predictable negative effect on the cosmetic appearance, but not on final function. This may be explained by the ability of the animal to compensate for length deficits of up to 15% by extending the shoulder and elbow joint.[26,27] Although small length deficits do not seem to affect functional outcome, the goal should be to restore antebrachial length completely.

Treatment of EI was successful, and no correlation was found between the initial amount of EI and final function. Nevertheless, EI was associated with progressive elbow OA, which may affect function on long-term evaluation. Although a dynamic proximal ulnar osteotomy was reported to be effective in treating EI because of ulnar length deficits, this method is not applicable for dynamical correction of EI in radial length deficits.[14] Again, it has to be emphasized that only the step defect between radius and ulna was treated and evaluated.

Malformation of the elbow joint was a common finding even after correction of EI. In view of this, the positive correlations between initial EI, FCP, and age versus final OA and the progression of pre-existing OA were to be expected. Furthermore, successful surgical removal of FCP and restoration of function will coincide with progression of elbow OA as we demonstrated before.[44] The present study suggests that correction of EI was most favorable in dogs at a young age, with remaining growth potential, without pre-existing OA, and without FCP. The growth potential of the adjacent epiphyses is proposed to be essential as an adaptive mechanism during correction of EI. In mature dogs, established malformation of the joint will lead to disappointing results. The negative correlation between the initial angular deformities and final elbow OA shows that dogs with more severe angular deformity in the antebrachium are less likely to develop elbow OA because of EI.

Carpal OA progressed despite correction of angular deformities. Carpal malformation could play an important role in this process. The initial ML angular deformity was demonstrated to have a larger impact on OA and presumably carpal malformation than CrCd carpal subluxation. The correlation between the amount of distraction and final carpal OA suggests that the tension on the flexor tendons and muscles may aggravate the progression of OA.[43] The progression of elbow and carpal OA is expected to have a negative effect on long-term function, but this observation was outside the scope of our study.

Initial elbow OA and initial function proved to be effective predictors of functional outcome, which is consistent with earlier reports on AGD and EI.[10,14] The final function was mainly dependent on elbow OA. Preventing elbow OA is therefore critical in treating dogs with developing AGD. The final cosmetic appearance was predicted by the amount of initial radial and ulnar length deficits and not by the angular and rotational deformities. Final cosmesis was mainly influenced by length deficits remaining after the lengthening procedure and carpal malformation.

Summarily, AGDs can be treated successfully with a CESF lengthening procedure despite small remaining length deficits. Treatment limitations are mainly determined by the pre-existing OA and malformation in the elbow and carpal joints. Initial elbow OA and initial function are prognostic factors in predicting functional outcome. The cosmetic appearance after treatment is determined by the magnitude of the initial radial and ulnar length deficits. Progression of elbow and carpal OA may have a negative effect on the long-term outcome of treatment of AGD.

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