Limb deformities in dogs: the role of the primary care veterinarian

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EPIDEMIOLOGY

Angular limb deformities are common in dogs. They are primarily seen in dogs of chondrodystrophic breeds. Chondrodystrophic dogs have a genetic make-up that leads to variable impairment of the growth of their appendicular skeleton and skull.[1] Their axial skeleton is spared. Most chondrodystrophic dogs have symmetrically deformed forelimbs and pelvic limbs. The forelimbs of chondrodystrophic dogs initially and primarily have a premature closure of the distal ulnar physes that may lead to a valgus (ie, abaxial or lateral) deformity, caudal angulation, and slight external rotation of the distal portion of the antebrachia originating at the distal radial physes. Most likely as a consequence of that primary closure, chondrodystrophic dogs often have a varus (ie, axial or medial) deformity originating at the proximal radial physes (Figure 1).

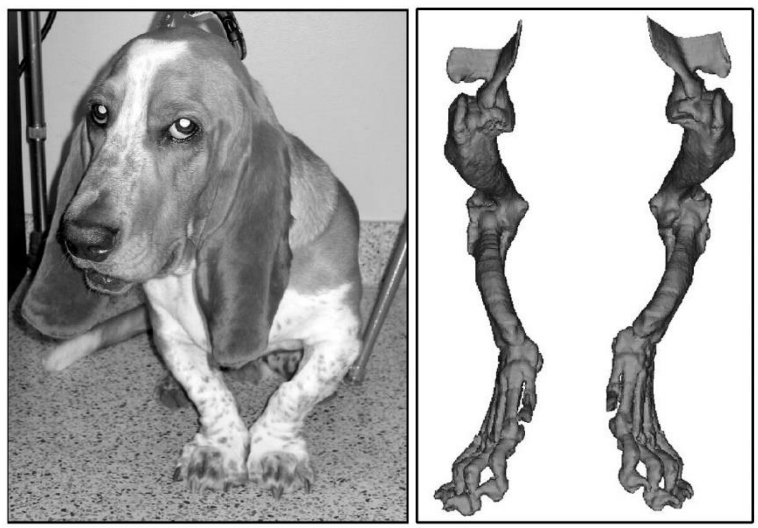


Figure 1. This 1-year-old Basset Hound (left) has a deformity of both forelimbs that includes valgus angulation of the distal portion of his antebrachia and varus angulation of the proximal portion of his antebrachia. These angulations are visible on a 3D rendering of his forelimbs that is based on a computed tomography scan (right).

The pelvic limbs of chondrodystrophic dogs also have angular and rotational deformities, specifically varus and caudal angulation and external rotation originating from the proximal portion of the tibiae, coxa vara, and medial patellar luxation. Breeders and owners of chondrodystrophic dogs anticipate a certain degree of curvature in the limbs of their dogs and they may not seek medical care to treat the consequence of these deformities unless the dogs are limping consistently.

Angular deformities occur as a result of injuries, most often injuries to growing long bone physes but also as a result of fracture malunions. Most angular limb deformities or traumatic origin affect the antebrachium, these deformities represent approximately 1% of the orthopedic problems of dogs.[2] These deformities may include valgus or varus angulation of variable severity. The purpose of this chapter is to review the assessment, therapeutic decision -making, and surgical management of canine angular limb deformities, particularly antebrachial deformities.

PREOPERATIVE ASSESSMENT

The preoperative assessment of patients with limb deformities is complex and includes a variety of factors: limb use and cosmesis, range of motion, static rotation, pronation, supination, medio-lateral (ML) and cranio-caudal (CC) angulation, length deficit, joint effusion, pain and osteoarthritis (OA) in the joints adjacent to the deformity. It is important to proceed with a complete assessment of deformity patients as rapidly as possible because growth and time will negatively impact the deformed limb. In a study, the average delay before the time of a deformity was noticed and the time corrective osteotomies were performed was 18 weeks.[3] Some clinicians have the misguided impression that *monitoring* (i.e., reevaluating every few weeks) a deformity is a valid form of management. This form of conservative management is rarely medically advisable. The owners' motivation when bringing patients with limb deformities is primarily enhancing limb use and function, but also enhancing overall mobility, alleviating limb pain, and improving limb cosmesis. Limb use, cosmesis, and overall mobility may be graded (Table 1).[3]

Table 1. Assessment of limb use, cosmesis, and overall mobility in patients with limb deformities.

	Limb use (lameness)	Cosmesis (difference with opposite limb)	Mobility (activity level, performance)
Excellent	None	None	Normal
Good	Mild, intermittent	Minor	Mild restriction
Fair	Constant	Significant	Severe restriction
Poor	Toe-touching to NWB	Major	Very limited mobility

Abbreviations: NWB, non weight-bearing.

It is critically important to make sure that these grades are agreed upon by owner and clinician to avoid discrepancies in perceived severity of the problem. Some owners underestimate the severity of the problem, others overestimate it. Angular limb deformities, for example, tend to be noticed later in life and underestimated in dogs with long or curly hair compared to dogs with short hair. Owners may underestimate the severity of a developmental humero-radial (caudo-lateral) luxation in a young puppy because they may perceive limb use as acceptable. Some owners are primarily motivated by limb cosmesis of their pets (i.e., show dogs). The optimal management of limb deformities will improve both function and cosmesis of treated patients.[3] Poor limb use per se is not a clear indication for surgery nor does not mean that one specific surgery should be performed. For example, a dog with an antebrachial deformity and a developmental humero-ulnar luxation leading to absence of ulnar trochlear notch may have poor limb function but may not be candidate for a corrective osteotomy. A dog with severe OA combined with an angular limb deformity may not function better if the deformity is corrected because of the presence of OA-induced pain. All measurements from the affected limb should be compared to measurements from the opposite limb, to measurements of dogs of similar age and conformation, or to values reported in the scientific literature.[4] The range of motion of affected limbs should be carefully assessed before surgery and the cause of any anomaly of motion should be understood before therapy is initiated (Figure 2).[4] Range of motion is an important aspect of the assessment of the affected limb because loss of joint motion may have a profound negative impact on limb use. For example, a dog with loss of carpal extension may not be able to bear weight on his forelimb. Loss of motion is common with developmental antebrachial deformities, particularly loss of carpal flexion as a result of a developmental subluxation and loss of elbow flexion as a result of humero-ulnar or humero-radial subluxation or OA.[3]

Angulation - Limb (radial) angulation is assessed in patients with limb deformities.[5] Valgus and varus ML deformities have a more significant impact on limb use than CC deformities because the forelimb has few adaptive options in adjusting for the presence of ML deformities compared to CC deformities, where an increase of decrease in elbow and should joint flexion may offset a deformity. When standing and walking, dogs most likely load their forelimbs, so the center of their shoulder joint and the metacarpal pad form a vertical line, as seen from the front of the dog. That line is named the ML mechanical axis of the limb (Figures 2 and 3). Having a vertical mechanical axis leads to the lowest energy expenditure and optimizes the effectiveness of locomotion.

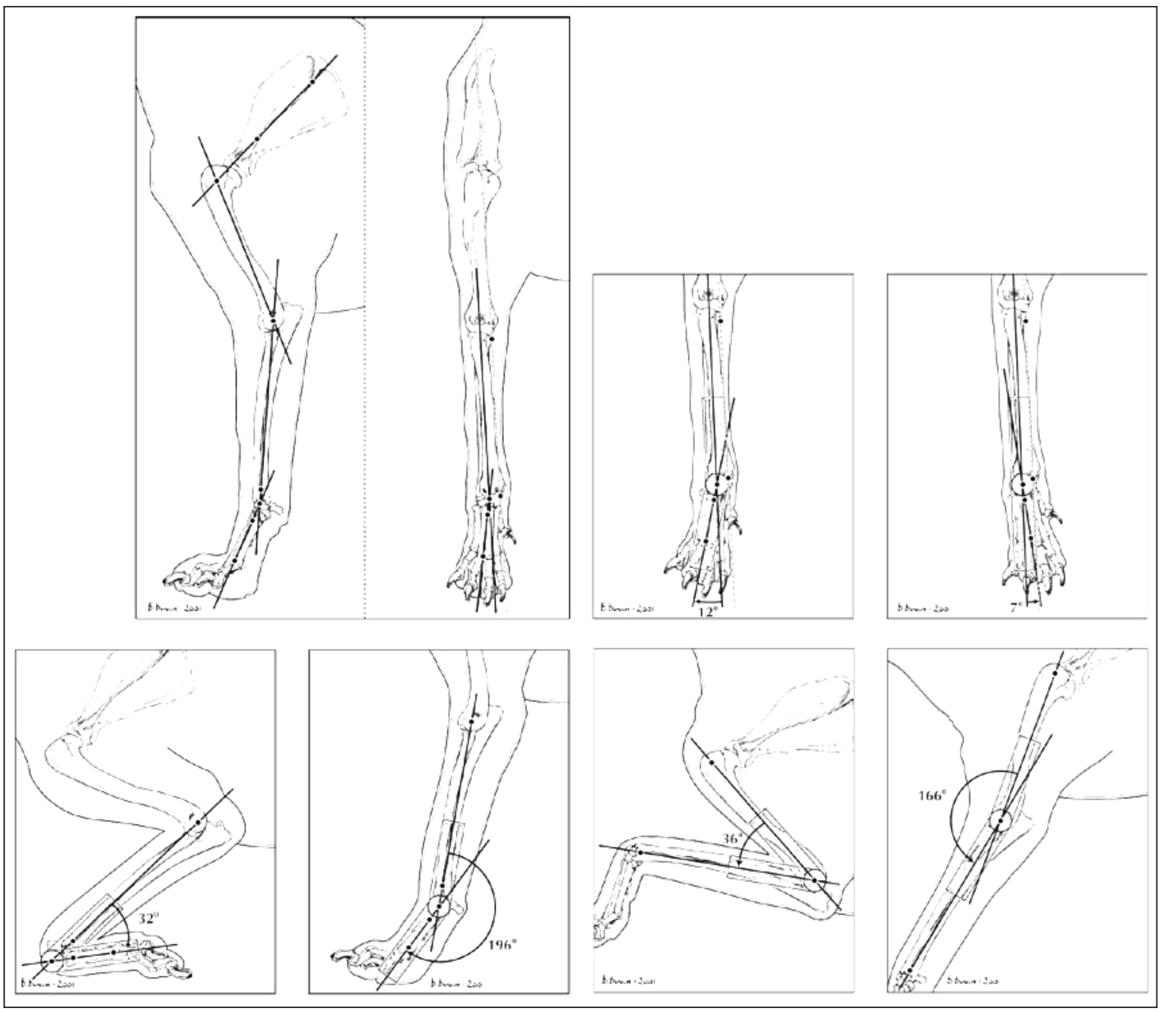


Figure 2. Normal range of motion of the carpus and elbow joint in Labrador Retrievers as measured using a plastic goniometer aligned with the metacarpal, cranio-caudal midpoint of the distal aspect of the antebrachium, lateral epicondyle, cranio-caudal midpoint of the proximal portion of the humerus, and spine of the scapula (upper left). Nineteen degrees of motion are available in a medio-lateral direction (upper right), 164° in a cranio-caudal direction for carpal motion (lower left), and 130° of elbow motion. (from Jaegger G, Marcellin-Little DJ, Levine D, Am J Vet Res, 63, 979-986).[4]

Valgus deformities are often visually more striking than varus deformities and may have a higher negative impact on limb use because the normal limb most often has 5 to 10° of valgus. For example, a medial deformity of 20° in a dog with an initial valgus of 10° will lead to a manus orientation of approximately 10°, a reasonably discrete deformity, but a lateral deformity of 20° will lead to approximately 30° valgus, a significant deformity. It is not possible to accurately assess CC angulation of the antebrachium during stance or palpation. It is assessed on radiographs. ML angulation should be assessed while the patient is not sedated and bearing weight on his affected limb. ML angulation during stance overestimates the actual angulation of the antebrachium, particularly in patients with valgus deformities because joint subluxation may occur in addition to bone angulation when the joint is loaded asymmetrically. Angulation may also occur when patients place their limbs in pain-relieving positions, to decrease the load placed on a joint or on part of a joint. ML angulation is also assessed when the patient is relaxed (often under sedation). ML angulation measured on a relaxed limb tends to be the most accurate assessment of limb angulation. While many patients have a single (unifocal) angular limb deformity, some patients have two (bifocal, Figures 1 and 4) or more complex angular deformities (Table 2). Others have a uniformly angled bone, resembling a bow, described as multifocal deformities.[5]

Table 2. Common components of classic canine antebrachial deformities.

Type of deformity	Length deficit	Angulation	Rotation	Other components*
Chondrodystrophy (mild)	None	U valgus, distal radius	External	Distal HU subluxation
Chondrodystrophy (severe)	None	U valgus, distal radius U varus, proximal radius	External	Distal HU subluxation
Chondrodysplasia	None	U valgus, distal radius U varus, proximal radius	External	Distal HU subluxation
Traumatic PPC, distal ulna	Mild	U valgus, distal radius	External	Distal HU subluxation
Traumatic PPC, distal radius, medial	Moderate	U varus, distal radius	Internal	Distal HR subluxation
Traumatic PPC, distal radius, lateral	Moderate	U valgus, distal radius	None	Distal HR subluxation
Traumatic PPC, distal radius, complete	Severe	None	None	Distal HR subluxation
Radial fracture malunion	Moderate	U valgus, radial midshaft	External	Synostosis
Osteochondrodystrophy†	Severe	U valgus, radial midshaft	External	None

Abbreviations: U, Unifocal; PPC, premature physeal closure; HU, humero-ulnar; HR, humero-radial.
* Other components assessed include: elbow and carpal subluxation and synostoses.
† Deformity associated with retained dwarfism, retained cartilaginous core, and hypertrophic osteodystrophy in skeletally immature dogs of giant breeds.

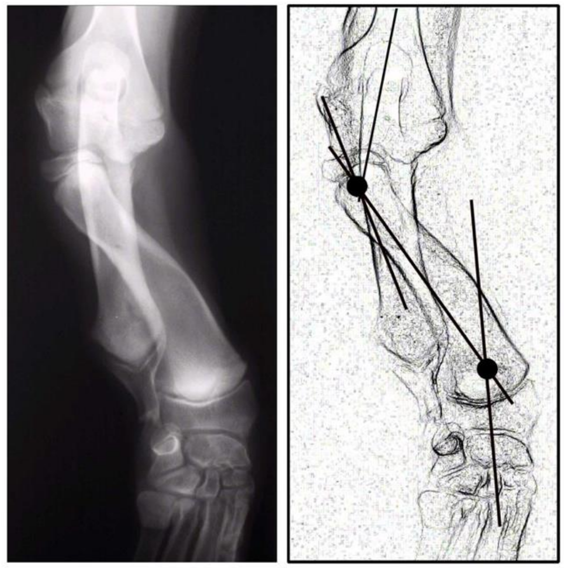
Rotation - Pronation (internal rotation) and supination (external rotation) are assessed preoperatively. This is primarily done to evaluate the antebrachium for the presence of restrictions in motion and synostoses. Synostoses are confirmed on radiographs. Synostoses, when present in patients with growth potential, may have devastating consequences on elbow joint congruity and, to a lesser, extent on carpal joint congruity. Synostoses are unusual in dogs with developmental antebrachial deformities resulting from premature closure of the distal ulnar and radial physis or resulting from chondrodystrophy. Synostoses are much more common in patients who previously underwent segmental ulnar ostectomies or in patients with prior radio-ulnar shaft fractures. Pronation and supination may also be used as a predictor of rotational deformities. Dogs have approximately 45° of rotational motion in their antebrachium, with a pronation of 0° and a supination of 45°. Cats have twice as much supination as dogs.

Figure 3. This Yorkshire Terrier has valgus deformity of the distal portion of the radius. On the right, dots have been placed on the approximate centers of the shoulder, elbow, carpus, and metacarpal pad. The centers of the shoulder joints and metacarpal pads appear to form a line perpendicular to the ground.

Rotational deformities are assessed preoperatively. Rotation is a common component of antebrachial deformities: valgus deformities are often associated with external rotation and varus deformities with internal rotation. Rotation is difficult to assess because the presence of angulation influences the perceived angulation of an extremity and because dogs may use their available pronation or supination to enhance their limb function and decrease their perceived pain. Dogs with severe valgus, for example, tend to purposefully externally rotate their limbs to improve the contact of their digits on the ground during stance. Looking at the direction of the footfall as a sole measure of rotational deformity is inappropriate because it greatly overestimates the rotation present in the antebrachium. Instead, rotation should be assessed on a relaxed (or sedated) patient by comparing the direction of the plane formed during flexion and extension of the carpus to the direction of the plane formed during flexion and extension of the elbow joint.[5] Rotational deformities cannot be reliably assessed on radiographs.

Length deficit - Radial length deficit is assessed on the patient by comparing the distance between the radial head, palpable proximally and laterally to the medial styloid process of the radius, palpable distally and medially. Ulnar length deficit is assessed on the patient by comparing the distance between the olecranon, proximally and caudally to the lateral styloid process, medially and distally. Length deficits are assessed more accurately on radiographs. Compensatory humeral overgrowth may be assessed on the patient by comparing the distance between the greater tubercle, proximally and cranially to the lateral humeral epicondyle, laterally and distally. If a humeral length discrepancy between the affected and control limb is suspected, it may be assessed more accurately on radiographs.

Figure 4. This dog has a bifocal angular radial deformity with a valgus deformity of the distal portion of the radius and a varus deformity of the proximal portion of the radius. The radial and ulnar physes do not appear closed.



Translation - Translation is a displacement of a limb segment in relation to another limb segment in a direction parallel to the long axis of that limb. Translation may be present as a consequence of a fracture malunion. It is rare in dogs. Dogs with severe caudad deformity of the radius originating in the distal portion of the bone compensate for these deformities by hyperextending their carpus. This results in a perceived caudal translation of the carpus in relation to the radius.

Joint subluxation - Careful assessment of the joints adjacent to the deformity should be performed. Joint effusion may be present as a consequence of a severe subluxation or cartilage damage. Crepitus may be present as a consequence of cartilage wear or osteophytes at the articular margins. A pain response may be suspected based on activity level, weight shift towards the opposite forelimb or away from the forelimbs, or during manipulation (flexion, extension, pronation, supination, valgus or varus stress). Assessing pain is critically important because the presence of pain suggest articular damage (cartilage erosion, synovitis, subluxation, OA) and that damaged should be assessed as objectively as possible and factored in the preoperative planning and surgical recommendations made to the owner. Subluxation and OA are confirmed on radiographs.

Radiographs are an important step in the assessment of antebrachial deformities. CC and ML views of the antebrachium are made and compared.[3] A magnification marker or object with known length should be placed along the antebrachium and be parallel to the plate when these radiographs are made using digital radiography in order to accurately calibrate these radiographs and assess length deficits. Radial and ulna length deficits are measured in millimeters and as a percentage of radial and ulnar length.[3] Dogs where a premature closure of the radius or the ulna precedes a premature closure of the other antebrachial bone have a larger deficit present in the bone responsible for the initial closure. For example, in a dog with primary closure of the distal ulnar physis and secondary closure of the distal radial physis may have a 10% length deficit in the ulna and a 4% length deficit in the radius. Understanding the primary closure site impacts the therapeutic decision. Radiographs are used to assess the shape of the radius and the ulna and the type (i.e., uni-, bi-, multifocal) and origin (i.e., proximal physis, shaft, distal physis) of the angular deformity in the ML plane. The radial angular deformities as in the ML and CC planes often have different origins. The classic angular deformity that results from chondrodystrophy, for example, includes a unifocal valgus deviation originating at the distal radial physis and a multifocal caudal deformity involving in the radial midshaft. Priority will be given to the ML angulation when planning the correction of antebrachial deformities because dogs can compensate for CC angulation much more than to ML angulation. The radiographic appearance of the radial and ulnar physes should be assessed on radiographs. Partial or complete closure may be seen. Interestingly, the correlation between growth potential and radiographic appearance of the physes is low. Some physes appear open but do not appear to lead to bone growth. Other physes appear closed but have appeared to contribute to bone growth (unpublished data). Radiographs are assessed for the presence of carpal and elbow joint subluxation or luxation (Table 3). Elbow (sub)luxation appears to have a larger impact on limb use than carpal subluxation and is easier to assess on radiographs. In experimental models of antebrachial deformities caused by premature physeal closure of the distal ulnar physis induced by submitting the distal portion of the ulna to high radiation doses, cartilage damage in the elbow joint occurs within two weeks of ulnar premature physeal closure (Figure 5).

Figure 5. A distal humero-ulnar subluxation is present in this dog with a premature closure of the distal ulnar physis (left). A distal humero-radial subluxation is present in this dog with a premature closure of the proximal radial physis (center). This dog with a premature closure of the proximal radial physis (right) has a severely abnormal trochlear notch.

Since conservative and surgical management of antebrachial deformities has a limited power in improving joint geometry (with the exception of circular external fixation, see below for additional information), it is critically important to address joint subluxation as rapidly as possible in skeletally immature patients with antebrachial deformities. The presence and severity of OA is also assessed on radiographs. Severe OA is irreversible and may limit the positive impact of corrective osteotomies. Its presence should be taken into account when choosing therapy. The presence, location, and length of a radio-ulnar synostosis should be assessed on the ML radiograph.

Computed tomography (CT) may be used to further assess the shape of a deformed antebrachium. The digital information contained in cross-sectional CT may be imported into computer-aided design (CAD) software to make 3D renderings (Figure 1). CAD is used to

Table 3. Common joint anomalies resulting from abnormal antebrachial growth.

Joint anomaly	Cause	Potential consequences
Distal humero-ulnar subluxation	PPC distal ulna	Ununited anconeal process, severe elbow OA
Distal humero-radial subluxation	PPC proximal radius PPC distal radius	Fragmentation of the medial coronoid process Severe elbow OA
Caudo-lateral radial luxation	Unknown	Severe elbow incongruity, loss of elbow flexion,
Proximal radio-ulnar subluxation	PPC distal ulna	Loss of carpal flexion, mild carpal OA

Abbreviations: PPC, premature physeal closure; OA, osteoarthritis.

enhance the contrast of these images, eliminate data collection artifacts (i.e., beam hardening in CT scans), and select specific information for the creation of specific 3D renderings (Figure 1). The 3D rendering is oriented in space and a support structure may be created. 3D renderings may be kept at their original size or may be resized. Making half size models requires only one eighth of the material required to make a full-size model because length, width, and depth are halved in a smaller model. Decreasing the size of the model may be necessary to make a model of a structure too large for specific manufacturing methods or to decrease the model cost. The creation of physical models based on 3D renderings is named free-form fabrication (FFF). Approximately 25 different types of FFF methods are used, making models ranging from wax to titanium. Stereolithography apparatus (SLA) was the first commercially available FFF method (Figure 6). SLA relies on an ultraviolet laser to cure a photopolymer. SLA is slow but precise. Its speed depends on the power of its laser beam. The maximal size of prototypes in SLA machines ranges from 250x250x250 mm to 500x500x500mm (VIPERsi SLA, 3D Systems, Valencia, CA). Please see expanded information on this topic in the general sessions of this conference.

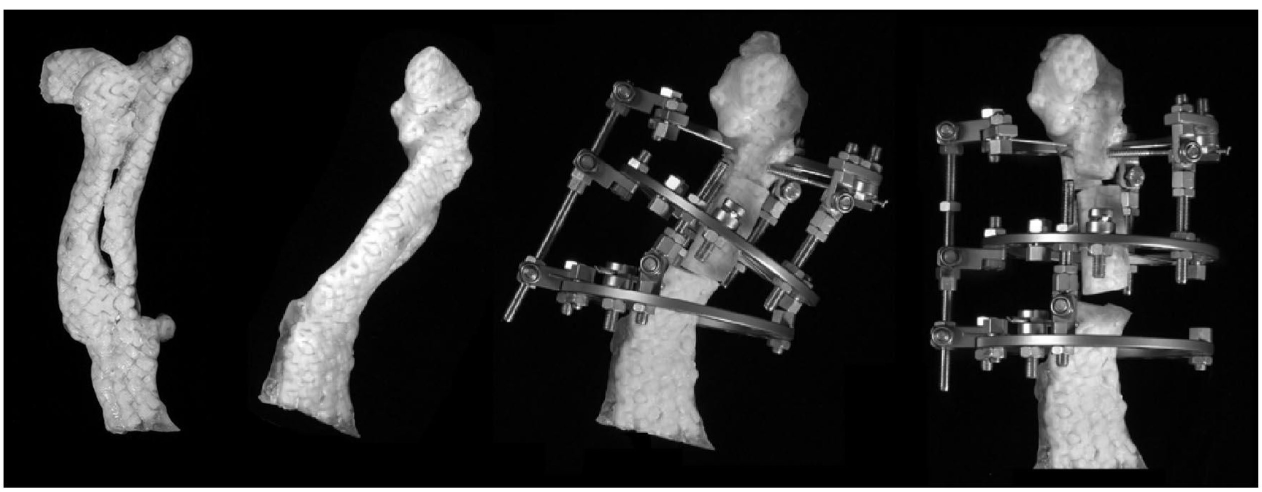


Figure 6. The 3D rendering in Figure 1 was used to make a full-size stereolithography model of the left forelimb of the Basset Hound using rapid prototyping methods. The model is used to assess the components of the deformity and to rehearse a corrective osteotomy. A circular external skeletal fixation frame with two sets of hinges allowing a simultaneous correction of both deformity with a single angular motor adjustment is placed on the model and adjusted to correct the antebrachial deformity

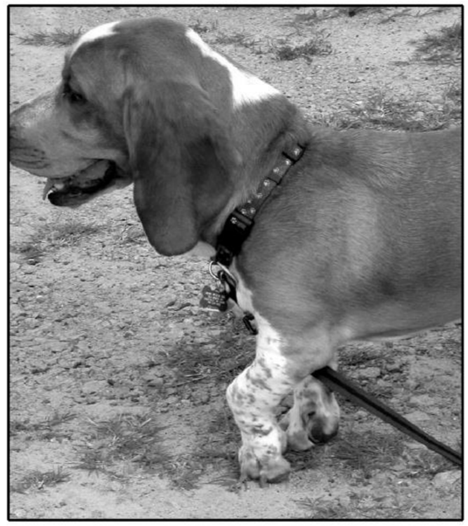
TREATMENT DECISIONS

Several options are available to help manage antebrachial deformities, ranging from conservative management to corrective osteotomies. The decision tree for management of limb deformities is complex.

Conservative management - Conservative management may be a valid option for the management of an antebrachial deformity if the patient has little or no residual growth potential, if joint subluxation is minimal, and if current limb use is deemed acceptable. As a general rule, conservative management is ineffective at improving limb deformities. Splinting is sometimes used with the intent to positively impact an angular limb deformity by protecting limbs from impact or limiting their future angulation or rotation. Splinting, however, has no proven efficacy and in the dog does not appear to offer clinical benefits to patients with angular limb deformities. Splinting also has side effects, it limits limb use, it promotes muscle atrophy, and it may lead to skin abrasions or necrosis. We do not recommend splinting patients with limb deformities. Specific threshold that could be used to recommend conservative management over surgical management are sometimes reported (i.e., 20% of limb length deficit) but do not have practical benefits in clinical patients because specific impairment to limb use result from the complex combination of angulation, length deficit, rotation, joint subluxation associated with the patient size, body conformation, and fitness level. It would be beneficial to determine the specific influences of these specific factors on limb use to predict whether surgical management would be indicated or not in dogs with developing deformities. For example, most Basset Hounds have severe antebrachial deformities resulting from their chondrodystrophic appendicular skeleton. Some Basset Hounds, however, have a combination of angular and rotational deformities that lead to hyperextension of their digits combined with a flexion of their carpus that leads to a significant impairment of these affected limbs (Figure 7). While their specific deformities most often resemble a classic form of chondrodystrophy, a small increase in angulation or rotation may lead to a dramatic decrease in limb use. While most Basset Hounds are managed successfully without surgery, some will benefit dramatically from a corrective osteotomy. Conservative management should be avoided in dogs with joint subluxation, even in the presence of seemingly acceptable limb use because the negative impact of joint subluxation on the articular cartilage is profound and occurs within two weeks after the occurrence of that subluxation.

Surgical management - Conservative management should also be avoided in dogs with deformities and with a large remaining growth potential because growth will most likely to lead to joint subluxation, and increase of the severity of the deformity. The presence of an angular limb deformity, even in the absence of limb disuse, predisposes the adjacent joints to the development of OA even in the absence of joint subluxation. This is likely due to the fact that with an angular deformity, abnormal stresses are placed on the articular cartilage of the joint adjacent to the deformity. The development of OA as a result of bone angulation has been reported in people with proximal tibial (varus) deformities and within seven months after the experimental creation of angular deformities in young dogs. It seems, therefore, indicated to discuss the consequence of angulation on the potential development of OA with owners, especially in large and giant breeds when large abnormal forces placed on articular cartilage may lead to OA.

Figure 7. Side view of the Basset Hound seen on Figure 1. Although his antebrachial deformities are similar in angulation and rotation between left and right forelimbs (see Figure 1, right) his left forelimb is often held in a position incompatible with comfortable weight bearing (right). While the right side may be managed conservatively, the left side will benefit from a corrective osteotomy.



Some surgeries are performed with the intent to promote corrective or compensatory growth. They generally rely on release osteotomies. Corrective growth is growth that leads to a decrease in abnormal limb angulation. It occurs when limb angulation occurs early in life. For example, if a 3-month-old puppy has a green-stick fracture leading to a 30° angulation of his radius, corrective growth will occur to decrease that angulation over time. To be effective, corrective growth requires a large growth potential. It appears ineffective in puppies more than 5 months old. Compensatory growth is growth that leads to a decrease in joint subluxation or limb length deficit. For example, in a puppy with premature of the distal radial physis occurring late in growth when growth potential is less than 5% of final bone length. Compensatory growth in the proximal radial physis may prevent the occurrence of a distal humero-radial subluxation. Compensatory overgrowth also occurs in bones adjacent to the bones with length deficits. For example, a dog with a short radius and ulna could have overgrowth of his humerus. In humans, overgrowth is a routine complication after fracture of long bones in children. Overgrowth after fracture has not been reported in dogs, to our knowledge. Ulnar osteotomies are a convenient, minimally invasive surgical option allowing corrective growth in young dogs with deformities and with a large remaining growth potential. The osteotomy should not be made near the elbow joint, where it could lead to a caudal displacement of the distal aspect of the proximal ulnar segment that would lead to elbow subluxation. The osteotomy should not be made too distally where it could lead to a weakness in the site of origin of the lateral collateral ligament. When an ulnar ostectomy is performed in a very young patient, the surgery should be minimally traumatic because a future surgery may take place in that site and minimal tissue changes will facilitate the future surgery, and because a radio-ulnar synostosis should be avoided. Bone healing will occur after most ulnar ostectomies. This healing may be delayed or stopped through removal of the periosteum during the procedure and through placement of a fat graft collected from the axilla. If the osteotomy heals prematurely, a decision should be made promptly to decide whether or not the premature healing predisposes the patient to long-term problems and interferes with future bone growth. A second osteotomy may be performed based on these factors. Short segmental ulnar ostectomies are most effective at addressing distal humero-ulnar subluxations compared to distal humero-radial subluxations. In my experience, it is fair to anticipate that distal humero-ulnar subluxations of up to 3 mm may be addressed though ulnar ostectomies. The corrective growth that will occur after an ulnar ostectomy is the result of the growth potential remaining in the radius at the time of the procedure. This means that ulnar ostectomies should be performed as early as possible when a premature closure of the distal portion of the ulna is diagnosed. Some surgeons perform radial osteotomies or ostectomies with the intent to decrease distal humero-radial subluxations. I do not recommend them because of the fact that it may lead to limb disuse, additional angular deformities due to malunion, or may fail to improve elbow joint congruity.

Periosteal stripping is more popular in horses than in dogs. The information regarding the specific benefits of periosteal stripping in dogs with deformities is scant. Periosteal stripping is based on the fact the thick periosteum present in puppies (the younger, the thicker) restricts longitudinal bone growth. Dogs may be candidate for periosteal stripping if they have a significant angular deformity in the absence of severe rotation or joint subluxation. I personally used periosteal stripping in two patients with acceptable results (unpublished data).

Surgical stapling has been used to restrict the longitudinal growth of one aspect of a distal physis, while the opposite aspect of that physis still grows. Staples are curved metal implants that bridge the physis. Staples are removed after a few weeks to avoid permanent growth cessation of the stapled side. Stapling has been effective in specific patients to induce corrective growth. These patients must be very young at the time of initial diagnosis; they must have a partial premature closure; they must not have subluxation of the joints adjacent to the deformity; and they should be followed carefully after the procedure to avoid under- or over-correction and to monitor complications.

Linear fixators may be used to correct deformities, when the deformity does not include a significant length deficit, when angulation and rotation may be acutely corrected during the procedure, and when subluxation is not present in the joint adjacent to the deformity. When acute corrections are performed, lengthening is often limited to the length gained through the angular correction. Anatomically, that length roughly equals half of the maximal gap present at the trans-cortex. Functionally, though, a limb may be longer once an angular correction is performed because the anatomic and functional axes of the limb are realigned after the correction of an angular deformity. Linear fixators do not appear to be very effective at correcting the cranio-caudal component of an angular limb deformity when treating antebrachial deformities. Attempting to distract a linear fixator may place a large amount of stress on the fixator and on the patient's soft tissue. The creation of a gap will also require the fixator to function as a buttress; therefore, increasing the bending and axial loads present at the osteotomy site. The practical consequences of that are the frames used for acute angular corrections should have flawless mechanical properties.

Bone plates may be used to treat antebrachial deformities when significant lengthening is not necessary and when the subluxation of adjacent joint does not require specific treatment. Bone plates are deceivingly simple in theory: the radius and ulna are osteotomized, the angular, rotational, and minor length deficits are corrected, and the bone is fixed in place with a plate. In large dogs, a plate may also be placed on the ulna. Like linear ESF frames, plates often have to be used in a buttress fashion when correcting antebrachial deformities, because the contact between bone ends is likely minimal after deformity correction. Unfortunately, the irregular nature of the bone surface require complex contouring of the plate a process easier to achieve in relatively small and thin plates but the buttress use of that plate requires the use of a relatively large and thick (i.e., stiff) plate. Bone plate fixation has significant limitations in patients with bifocal (varus, proximally and valgus, distally) deformities because the optimal correction of these deformities requires a proximal and distal osteotomy while the optimal plate placement requires a single midshaft osteotomy.

Circular external skeletal fixation frames are the most versatile method used to treat antebrachial deformities in dogs. This is due to the fact that circular ESF may be used to simultaneously correct angulation in one or two locations in a deformed bone, eliminate a length deficit, eliminate a rotational deformity, and decrease the subluxation present in adjacent joints.

In some patients with limb deformities, however, simpler management methods may be used to help treat limb deformities. With circular ESF, the frame consists of rings connected together by threaded rods. The method for placement of circular ESF frames is termed the Ilizarov method, from the name of the Russian surgeon who popularized the method. The frame is fixed to the bone with tensioned small diameter wires and, potentially, with half-pins. Circular ESF offer unlimited geometric adaptability. The ring size and number, threaded rod size, length, and number, and wire size, number, and orientation can by tailored to the purpose of fixation and the anatomy of the patient. The circular ESF systems with widest use are the Small Bone Fixator and the Circular External Skeletal Fixation system.[5,6] Linear and circular ESF frames may be combined to form hybrid ESF frames. Unifocal deformities are the simplest deformities to treat. Multifocal deformities tend to be treated like unifocal deformities by focusing of realigning the proximal and distal joints.[5] Bifocal deformities are most challenging to address because they generally are the combination of a proximal and distal physeal deformity, potentially in short bones. Their treatment potentially requires making two independent juxta-articular osteotomies and angular corrections (Figure 6).

Circular external fixators are made of individual parts that can be assembled into an unlimited number of configurations. Ilizarov frames can be used to treat bone deformities and fractures, to perform arthrodeses, to transport bone segments, and to treat joint contractures, with varying frame configurations. Ilizarov frames have been used in multiple species ranging in size from the rat, used as an animal model for research, to the horse. Most frame components remain constant, regardless of the use of the frame and the size of the patient. These components include fine wires, fixation elements, supporting elements, connecting elements, assembly elements, and sliding elements. Tensioning devices and wrenches complete the Ilizarov instrumentation.[7,8] The fines wires used with the Ilizarov method have a diameter ranging from 1.0 to 1.6 mm in animals and 1.5 to 2.0 mm in man. One-millimeter-diameter wires are used in dogs weighing less than 10 kg, 1.2-mm-diameter in dogs weighing 10 to 20 kg, and 1.5-mm-diameter in dogs weighing more than 20 kg. Different wire points are available: half-point, bayonet point, or trocar point. Wires with optimal bone penetration should be used in order to minimize thermal trauma to the limb. In our clinical experience, the half-point wires have the best bone penetration. Half-point wires Olive wires, also called stopper wires, have a larger diameter ball in their midpoint. They can be used to prevent translation of the bone fragment on the wire. When two olive wires are placed on opposite sides of the bone across a fracture site, the bending strength of the bone-frame construct is increased. Twisted wires or bent wires can potentially be used as an alternative to olive wires.

However, they have several disadvantages: they are weaker and may be difficult to remove once bone healing is complete and bone growth surround the twisted portion of the wire. Fixation elements allow wire fixation onto the Ilizarov frame. They include cannulated bolts, with a central hole or slotted bolts with an eccentric slot. The wires should always be kept straight to avoid frame migration, wire rupture, bone stress, or potential fracture during wire tensioning. When placing a wire, a cannulated bolt is used on the near side, the wire is then placed through the limb, and a cannulated or slotted bolt is used on the far side. Washers can be used to offset the wire from the ring by 1 millimeter or more or to potentially connect a wire to a connecting rod. The supporting elements include rings, plates, and posts, where the bolts attach. The rings are currently available with inside diameters ranging from 40 mm to 120 mm. For the Small Bone Fixator system (SBF, Hofmann srl., Monza, Italy), nine ring sizes are available in 10 mm increments. For the Circular Fixator system (IMEX, Inc., Longview, TX), four ring sizes are available. They are made of stainless steel, aluminum, or carbon composite material. A space of no less than one centimeter should be present between the inside edge of the rings and the skin. Partial rings should be used on the flexion side of joints to allow unrestricted range of motion after frame placement. Plates and posts are used to offset wires from rings to fix short bone fragments. The connecting elements connect the supporting elements. They include threaded and telescopic rods. The diameter of the rods determines the size of all other Ilizarov elements. Four-, 5- or 6-mm-diameter rods are commercialized. Their pitches are 0.66, 0.8, and 1 mm, respectively. Their length ranges from 30 to 200 millimeters. Five-millimeter systems can be used in cats and dogs of all sizes. Six-millimeter systems can be used in man and in medium to giant dog breeds. At least three connecting rods are used to connect the rings. With hinged fixation, two connecting elements have hinges and a third element, used for distraction, is named the angular motor. Hinged connecting rods are made with two male posts rotating around a bolt. The angular motor is connected to the ring with two twisted plates. With conventional, straight Ilizarov fixation, all connecting rods can be used as linear motors for distraction. The assembly elements include bolts and nuts used to assemble supporting elements and connecting elements. Some nuts have dots or marks on their faces to facilitate adjustments. With hemispherical washers, the direction of the connecting rods in relation to the rings can vary. This feature is helpful when ring fixators are used for fracture repair. Nylon-insert nuts may be used to secure hinges and other points of rotation. The sliding elements include buckles. Originally, the buckle was Ilizarov’s first fixation element. Buckles are now mainly used as points of rotation between two rings. Tensioners are used to tension the wires. They come in multiple forms: mechanical and pneumatic. They are a critical part of the Ilizarov instrumentation. No tension is placed in animals weighing less than 1 kg. Twenty to 30 kg of tension is placed in animals weighing 5 to 10 kg, 30 to 60 kg in animals weighing 10 to 20 kg, and 60 to 90 kg in animals weighing more than 20 kg.[9] Graduated and non-graduated tensioners are available but only graduated tensioners provide information on the amount of tension placed on the wires. Box wrenches and flat wrenches are used to perform frame adjustments. Seven-, 8- and 10-mm wrenches are used with 4-, 5-, and 6-millimeter systems, respectively. Although they were not part of the original Ilizarov instrumentation, fixation cubes have been developed to connect half-pins to the rings, creating hybrid frames. Half-pins can be added to the frames to enhance fixation of short bone fragments or to fix partial rings to the proximal part of the humerus and femur, where full rings cannot be used. To our knowledge, five manufacturers make circular external fixation systems of variable complexity for canine use. Four systems are made in Europe (two in Italy, one in France, and one in England) and one in the United States of America.

Ilizarov frames should be built so dogs can bear normal weight after frame placement. The frames should have four rings, whenever possible. The outer rings should span the bone and the inner rings should be close to the fracture or osteotomy site, creating a "far-near-near-far" pattern. The specific frame design has been described in detail in several reports.[3,5,8] This include choosing the number of rings, their size, their type, the type of hinge or hemispheric washers, their location, the number and location of osteotomy, the type and location of wire and pin fixation, the presence of sliding or traction components for correction of correction of elbow joint subluxation. Partial rings, placed of the flexion side of joints, decrease the interference of the frame with normal joint range of motion. The rings should have the smallest diameter that maintains a centimeter-wide gap between their inside edge and the skin.

Circular external fixators are particularly complex. Having a comprehensive preoperative planning enhances case management by: 1.requiring a full understanding of the current pathophysiology and its anticipated evolution, 2. requiring evaluation of all anatomical constraints, 3. requiring evaluation of the biomechanical characteristics of the situation, 4. ensuring availability of frame components, and 5. decreasing surgical time. The preparation of hinged frames ideally includes a drawing including a cross-section of the limb at the level of the planned osteotomy, the ring, the hinges, the angular motor, and the wires.[3] With advances in 3D data collection and rapid manufacturing methods, digital images of affected bones may be collected and used to make models. These models may be used for operative rehearsal. We currently make models for complex multifocal bone deformities using helical CT scanning and stereolithography, ink-jet, or electron beam melting rapid prototyping methods (Figure 6).[10] These models appear to improve the accuracy of diagnosis and the precision of the surgical placement and postoperative corrections. They also appear to decrease the duration of surgery. Silicon molds of first-generation models may be made to reproduce bones of interest for educational or experimental use.

Ilizarov frames have the advantage to be relying on tensioned fine wires with a diameter ranging between 1.0 to 1.6 mm in small animals and ranging between 1.5 to 2.0 mm in man. Even though these fine wires are less disruptive than conventional external fixation pins with a larger diameter, they have to be placed carefully to optimize the biomechanics of fixation while minimizing soft tissue interference or potential injury. As a general rule, patients should be able to function normally while the fixator is in place. This is only possible when the fixator is stable and when neurovascular bundles and major muscle groups are unaffected by the transosseous wires. The frames should not interfere by the skin of the limbs, axilla, or groin, during locomotion. It is imperative to leave at least a one-centimeter space between the skin and the inside edge of the rings to avoid skin irritation and necrosis. In small animals, the placement of full rings around the limbs is limited to the radius and tibia, and, in some instances, the distal portion of the humerus and femur. As a consequence, the use of conventional Ilizarov frames, with two rings above and below the osteotomy or fracture site, is limited to the radius and tibia. Partial rings are often used on the flexion side of joints, with a cranial opening for the proximal aspect of the radius and caudal opening on the proximal aspect of the tibia. The principles of Ilizarov fixation can be applied to the femur and humerus but the frames have to be modified to include arches, plates, and cubes for half-pin fixation. These hybrid frames are very challenging to conceive, to place, and to maintain.

Few reports provide information about wire placement in small animals. Marti and Miller reported on safe, hazardous, and unsafe corridors for placement of linear external fixators.[11,12] Putod described the cross-sectional anatomy of dog limbs. Software packages with cross-sectional and 3-D anatomic representations are becoming available for human anatomy and, to a lesser extent, for dogs. The medial aspect of the radius is safe, distal to the insertion of the pronator teres muscle (distal two thirds of the bone). Laterally, the radial head can be palpated subcutaneously. The lateral aspect of the radial shaft is a hazardous corridor, because of the presence of the extensor muscles. The radial nerve is on the caudo-medial aspect of the limb. Practically, wire placement in the radius is cranio-medial to caudo-lateral and caudo-medial to cranio-lateral, with wire angles of 90° in the distal third and 45 to 60° in the proximal two thirds. When hybrid fixation is made necessary by the presence of a short bone fragment, half-pins can be placed in the distal part of the radius, caudo-medially, medially, or cranio-medially, or in the proximal part of the radius, laterally. Wire placement through the proximal part of the radius in a cranio-caudal direction, in a slightly laterally offset position, has been described (by Dr. Yves Latte), but is not used by the author. This wire placement has several drawbacks: trans-fixation of the extensor muscles and trans-fixation of the ulna, eliminating the ability to pronate and supinate. In our experience, the clinical function is better if trans-fixation of the ulna should always be avoided, because the elimination of pronation and supination appears to negatively impact limb use and also appears to lead to premature pins and wires loosening. The ulna has two safe zones: the olecranon, proximally and caudally, and the lateral styloid process, distally and laterally. Wire placement in the ulna is generally limited to wires used for displacement of the ulna in relation to the radius. One or two wires can be placed on posts, from a medial to lateral direction, across the caudal aspect of the proximal portion of the ulna. The posts can be adjusted progressively to treat proximal or distal humero-ulnar subluxations.

Ferretti designed the SBF fixator and was the first clinician who used the Ilizarov method in veterinary medicine. He established guidelines for wire size and tension. Wire tension should not exceed 30 kg when the wires are placed on partial rings or posts, away from the rings. Several biological factors strongly influence the stability of Ilizarov frames. For deformity correction, the preservation of the periosteum helps the stability at the osteotomy site. The callus or new bone regenerate helps creating an internal support for the bone (bio-buttress). The bone healing rate at the osteotomy site is increased by the presence of an increased blood supply at the osteotomy site (young dogs, large bone, and metaphyseal osteotomy), a minimally traumatic osteotomy, a long resting period after osteotomy and before distraction, a small amount of daily distraction, and a high frequency of distraction. For fracture treatment, bone healing seems enhanced when fractures are treated closed. Enhanced bone healing also creates a beneficial bio-buttress. Sharp wires are used to decrease thermal trauma to the limb. The wires are placed with a low-speed power drill. A 2 to 3-mm-long skin incision may be made at the entry and exit sites of the wires to decrease skin trauma. The author has abandoned the use of such incisions. Drilling is generally started on the side of the bone that provides maximal control for wire positioning and safest wire placement - the medial aspect of the radius and tibia. Once the transcortex has been pierced, the wire can be tapped with a mallet to avoid rotation of the wire through the tissues on the opposite side of the limb. The use of a drill with an oscillating function also helps protecting soft tissues. The soft tissues can be gently reflected by digital pressure. Tension should not be present on the skin after wire placement. If tension is present, the wires may be moved below the skin surface and a new hole in the skin may be made with a more relaxed skin placement. A releasing incision may also be made in the skin to eliminate a minor amount of tension

POSTOPERATIVE MANAGEMENT

The postoperative management of dogs after surgical correction of antebrachial deformities focuses on wound care, maintaining limb use, avoiding excessive stress placed on the bone and external fixation frame, and maintaining range of motion in the carpus and elbow joints. It is important to maintain limb use during the early postoperative period by giving pain medications, rapidly eliminating swelling, using protected weight shifting and weight bearing exercises, and avoiding trauma. Swelling may be present in the extremity and around the surgical site in the early postoperative period, particularly in patients undergoing intraoperative de-rotation of their extremity. Swelling in controlled by enhancing lymphatic and venous drainage through elevation of the extremity, passive range of motion of the carpus, gentle finger massage (effleurage), and cold therapy. Swelling is most often eliminated in two to three days. In patients with circular external fixators undergoing distraction osteogenesis, distraction starts on the third day after surgery.[3] Distraction tends to increase tissue tension and leads to loss of range of motion, particularly carpal joint motion, in the late treatment stages. The distraction rate is often decreased when tissue tension increases, and activities promotion joint motion and stretching are routinely performed. Bandages and braces may be used to regain lacking joint motion in specific instances.

The soft tissue complications of Ilizarov fixation are comparable to the soft tissue complications of conventional external fixation. In most cases, the complications are a consequence of improper surgical technique. Neuropraxia results from nerve trauma. Hemorrhage can result from a vascular injury. In most cases, hemorrhage is intraoperative, but it may occur several weeks after surgery, when wires abrade blood vessels. Skin irritation or necrosis can result from ring placement in contact with the skin or from the contact of the frame with the groin or axilla. Focal drainage occurs at the skin wire interface, especially when wires are loose. Muscle contracture may result from decreased limb use or from the tension generated during limb lengthening. In our experience, the soft tissue complications associated with Ilizarov fixation are common, but they generally are minor and rarely affect the outcome of surgery.

Rotation is most often corrected acutely, intra-operatively. Angulation is most often corrected first, progressively after surgery. Mild lengthening is combined with angular correction is dogs likely to heal rapidly (i.e., young dogs). Lengthening is accelerated after angular correction is complete, generally 15 to 30 days after surgery. The distraction rate is often 1 to 2 mm per day at the point of maximal distraction, divided in two to four increments. [3] Radiographic follow-up is done at the end of angular correction, and every three to four weeks afterwards until bone healing is complete. Circular external fixation frames are removed under sedation. The long-term outcome of the correction of antebrachial deformities has been good to excellent, from cosmetic and functional standpoints.[3,8] Circular ESF has been used to treat antebrachial deformities that include a severe elbow joint subluxation, a limb length deficit, and an angular limb deformity of the distal portion of the radius and ulna. Placing a circular external fixator with a single set of hinges and making two osteotomies (one used to correct angulation and limb length and one to eliminate elbow joint subluxation) had led to excellent clinical results. Distal humero-radial subluxations of up to 13 mm have been reduced using this method in five dogs. Circular ESF has been used to treat bifocal antebrachial deformities that include a severe varus deformity of the proximal portion of the radius and a valgus (generally combined with a multifocal caudal deformity) of the distal portion of the radius (Figure 6).

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