

Management of Humeral and Femoral Fractures in Dogs and Cats With Linear-Circular Hybrid External Skeletal Fixators

Linear-circular hybrid fixators were used to stabilize humeral and femoral fractures in 21 dogs and five cats. Twenty-two of 24 fractures with sufficient follow-up radiographic evaluation obtained union. Time to radiographic union ranged from 25 to 280 days (mean $\pm$ standard deviation [SD] 110 ± 69 days; median 98 days). Eleven animals developed minor and two dogs developed major pin and/or wire tract inflammation. Functional outcome was rated as excellent ($n=16$), good ($n=5$), and fair ($n=3$) at the time of final long-term assessment (range 4.5 to 60.0 months; mean $\pm$ SD 28.4 ± 15.4 months; median 28.5 months). Follow-up information was unavailable for two animals. Hybrid fixators were useful constructs for stabilization of humeral and femoral fractures, particularly fractures with short, juxta-articular fracture segments. *J Am Anim Hosp Assoc* 2008;44:180-197.

Kristin A. Kirkby, DVM, MS

Daniel D. Lewis, DVM,
Diplomate ACVS

M. Pilar Lafuente, DVM, PhD

Robert M. Radasch, DVM, MS,
Diplomate ACVS

Noel Fitzpatrick, MVB, Cert SAO,
Cert VR, MRCVS

James P. Farese, DVM,
Diplomate ACVS

Jason L. Wheeler, DVM, MS,
Diplomate ACVS

Jorge A. Hernandez, DVM,
MPVM, PhD

RS

From the Departments of Small Animal Clinical Sciences (Kirkby, Lewis, Lafuente, Farese, Wheeler) and Large Animal Clinical Sciences (Hernandez), College of Veterinary Medicine, University of Florida, 2015 SW 16th Avenue, Gainesville, Florida 32610; Dallas Veterinary Surgical Center (Radasch), 4444 Trinity Mills Road, Suite 203, Dallas, Texas 75287; and Orthopedic and Neurology Referrals (Fitzpatrick), Tilford, Farnham, Surrey, United Kingdom GU102DZ.

Introduction

Circular external skeletal fixation has become a well-established treatment modality for performing limb lengthening, bone transport, and progressive correction of limb deformities in dogs and cats.¹⁻⁵ In these dynamic applications, frame components are manipulated during the convalescence period to sequentially adjust the position of bone segments, invoking the phenomenon of distraction osteogenesis.^{5,6} When applied in a static mode, circular fixators can also be used effectively for fracture stabilization.^{7,8}

Circular fixators share many attributes with linear fixators, which make both systems advantageous for fracture management in dogs and cats.⁷⁻¹¹ Both systems are modular, allowing frames to be constructed in numerous configurations; they can be applied either during open or closed fracture reduction; they are particularly useful for stabilizing comminuted fractures; and they can be used in combination with internal fixation, most often intramedullary pins and cerclage wires.

Traditional circular fixators utilize small-diameter wires as fixation elements, whereas linear fixators utilize larger diameter full- and half-pins as fixation elements.¹² Although fixation wires are usually tensioned to increase construct stiffness, deflection of the wires during weight-bearing allows for axial micromotion of the secured bone segments. This purportedly stimulates callus formation and accelerates bone healing.^{13,14} Additionally, the use of small-diameter wires also facilitates placement of multiple fixation elements about the circumference of the ring at divergent angles, which is particularly advantageous when stabilizing short, juxta-articular bone segments.^{3,8,12} Manipulation of fixation wires, particularly olive wires, can help obtain or improve reduction either during or following surgery.^{8,11}

Application of traditional circular fixators is limited proximal to the elbow and stifle, as the proximity of the trunk interferes with placement of complete rings. A linear-circular hybrid fixator system^a has been developed that confers beneficial properties of both linear and circular systems.⁹ The principal connecting elements in this hybrid system are the partially threaded titanium hybrid rods. The threaded portion of the hybrid rods can be secured to the holes in ring components. Paired hemispherical washers and nuts can be used to secure the hybrid rods at an

oblique angle to the ring's surface. Linear fixator pin clamps^b are used to secure half- or full-pins to the unthreaded portion of the hybrid rod.^{9,15} Hybrid fixators allow utilization of ring components for stabilizing proximal limb fractures. They are simpler to apply, particularly in smaller dogs and cats, and they have fewer wire tract complications than traditional circular fixators.⁹ The purpose of this study was to review results from cases (21 dogs and five cats) in which hybrid constructs were utilized to stabilize humeral or femoral fractures.

Materials and Methods

The medical records and radiographs of all dogs and cats with humeral or femoral fractures managed with a hybrid fixator between June 2000 and July 2006 were reviewed. The following information was recorded for each case: the animal's signalment and history; a description of the fracture, including the degree of comminution (modified Winquist-Hansen comminution score;⁸ see Appendix); a description of the surgical procedure and related postoperative complications; the time to radiographic union as well as fixator removal; and the final clinical outcome.

All animals received perioperative cefazolin^c (22 mg/kg intravenously) at the time of anesthetic induction and every 2 hours throughout the surgical procedure. The affected limb was clipped and prepared for aseptic surgery. Fracture reduction was accomplished using an open, limited open, or closed approach. Anatomical reconstruction of the fracture was performed, when applicable, using interfragmentary cerclage wires, Kirschner wires, and/or lag screws. In most fractures, an intramedullary pin was placed. Bone grafts were utilized depending on the degree of comminution, the etiology of the fracture, and the discretion of the attending surgeon. Following closure of the surgical approach, an incomplete ring was secured to the juxta-articular, generally distal bone segment using various combinations of pins

and/or Kirschner and/or olive wires. When available, intraoperative fluoroscopy was used to confirm fracture reduction and proper application of the fixation elements. The primary hybrid rod was then secured in one of the lateral holes of the ring, using paired hemispherical washers and nuts. A variable number of partially threaded half-pins were placed to secure the longer, generally proximal bone segment. A secondary hybrid rod was secured to one of the cranio-medial holes of the ring by means of articulated posts or a hinge assembly, and the secondary rod was articulated proximolaterally to the primary hybrid rod or secured to a cranially positioned half-pin placed in the proximal fracture segment. If an intramedullary pin was used to stabilize the fracture, the end of the pin was left protruding proximally through the skin and articulated with the hybrid frame [Figures 1A-1D].

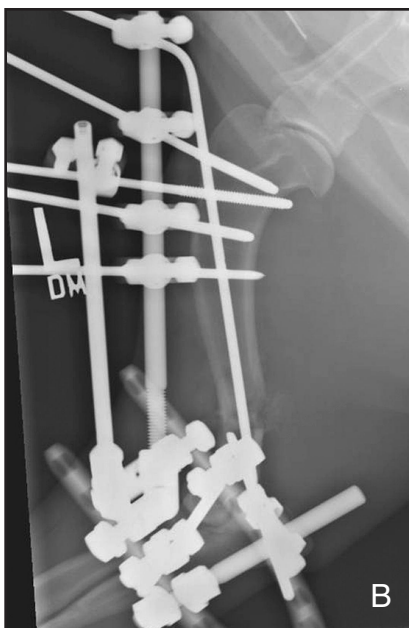
If a closed reduction was performed, the ring component was secured to the short fracture segment using pins and/or wires. Correct placement of the ring fixation elements was confirmed with fluoroscopy, when available. The primary hybrid rod was loosely secured in one of the lateral holes in the ring using paired hemispherical washers and nuts. A partially threaded half-pin was placed in the long, generally proximal fracture segment and was loosely attached to the hybrid rod using a pin fixation clamp. The fracture was then reduced by applying traction between the ring and the fixation pin. When the fracture was perceived to be aligned, the nuts securing the hybrid rod in the ring and the pin fixation clamp were tightened. Reduction was assessed by palpation or fluoroscopy, when available, and further manipulation was performed to improve reduction, if necessary. Once acceptable reduction of the fracture was achieved, the construct was completed by placing additional fixation pins and connecting elements as described for fractures treated with an open approach [Figures 2A-2F].

Appendix

Modified Winquist-Hansen Classification of Fracture Comminution

Score	Description
0	No comminution
I	Small, unimportant bone chip
II*	>50% contact between major proximal and distal fracture segments
III*	<50% contact between major proximal and distal fracture segments
IV*	No contact between major proximal and distal fracture segments
V	Segmental fracture

* Based on potential contact between segments following fracture reduction



Figures 1A-1D—Initial postoperative (**A, B**) radiographs showing stabilization of a distal diaphyseal-metaphyseal (Winquest II) humeral fracture (case no. 14). The intramedullary pin was left protruding from the proximal humerus, bent, and articulated with the hybrid frame. The fracture obtained radiographic union (**C, D**), and the fixator was removed 126 days following surgery.

Postoperative radiographs were obtained and adjustments were made, if necessary, while the animals were under general anesthesia. The limb and fixator were coapted, and the bandage was changed daily until perioperative swelling had resolved and the pin and wire insertion incisions had begun to heal. At the time of discharge, owners were instructed to clean the pin and wire tract-skin interfaces daily, restrict exercise, and administer nonsteroidal antiinflammatory medication for a variable period of time. Recheck examinations and radiographic assessments were advised monthly until fracture healing was complete and the fixator was removed.

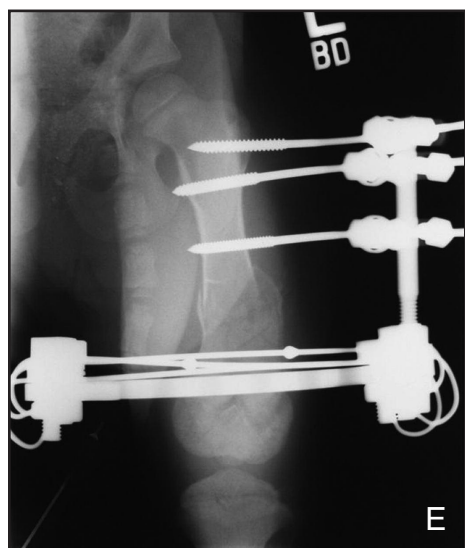
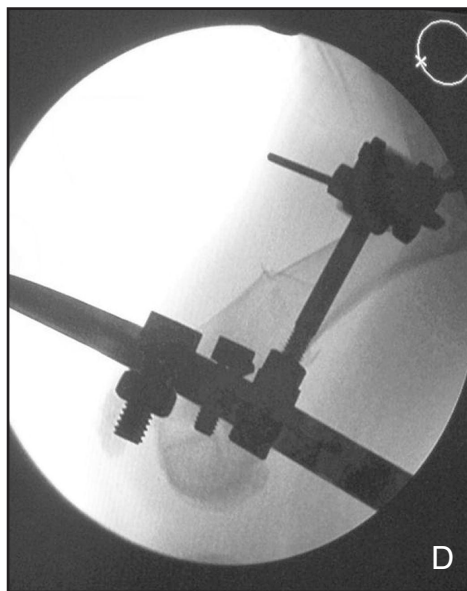
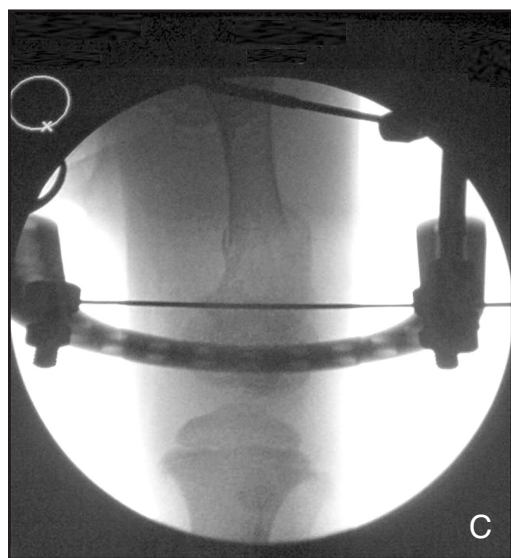
Operative reports and radiographs were reviewed, and the implants and hybrid configurations applied were recorded. Medical records and radiographs of each animal were reviewed to evaluate clinical presentation, complications, time to union, and time to fixator removal. Owners were contacted by phone and asked to describe their animal's long-term limb function based on the following scale: excellent (normal limb function); good (mild, intermittent lameness); fair (mild to moderate lameness, but consistent weight bearing); and poor (nonweight-bearing lameness).¹⁶

Statistical Analysis

Cox proportional hazards regression analysis was used to assess the effect of selected parameters on time to union.



Figures 2A-2F—Preoperative (A, B) radiographs of a transverse comminuted (modified Winquest-Hansen comminution score II) mid- to distal diaphyseal femoral fracture (case no. 10). The fracture was stabilized using a closed reduction. Fluoroscopy was used to confirm proper implant placement (C) and fracture alignment (D). Initial postoperative (E, F) radiographs were obtained.



Parameters assessed included age (<60 months versus >60 months); approach (open versus limited open or closed); articular component to the fracture (yes versus no); bone fractured (humerus versus femur); postoperative complications (none versus minor versus major); use of a bone graft; anatomical reduction (complete or partial reconstruction versus no reconstruction); initial versus revision surgery; and modified Winquest-Hansen score (0, I, or II versus III or IV). Parameters with a *P* value <0.20 were further examined in a multivariable model to evaluate possible interaction or confounding effects that these parameters might have had on time to union. Adjusted hazard ratios (HRs) and 95% confidence intervals (CIs) were reported in the final model for each parameter. The reference category had an HR of 1. An HR <1.0 indicated that the probability of union was decreased compared to that for animals in the reference category. Values of *P*<0.05 were considered significant.

Results

Fracture stabilization was performed in 21 dogs and five cats. Information regarding each animal's signalment and history, fracture description, complications, time to radiographic union and fixator removal, and final clinical outcome are listed in Table 1. The animals ranged in age from 3 months to 11 years (mean $\pm$ standard deviation [SD] 3.6 ± 2.6 years; median 3.5 years). Body weights for the dogs ranged from 4.6 to 54.0 kg (mean $\pm$ SD 20.6 ± 13.3 kg; median 22.0 kg), and body weights for the cats ranged from 3.0 to 6.0 kg (mean $\pm$ SD 4.8 ± 1.1 kg; median 5.0 kg).

Fourteen animals had humeral fractures, and 12 had femoral fractures. In 19 animals, fractures involved the distal diaphysis or metaphysis. The proximal to mid-diaphysis of the humerus was affected in three animals, and the proximal femoral metaphysis or diaphysis was affected in four animals. Five animals had open fractures, all as a result of gunshot injuries.

Five dogs had concurrent orthopedic injuries. Case no. 2 had ipsilateral tarsal ligamentous instability and a mandibular symphyseal fracture, which were stabilized with a circular external skeletal fixator and a cerclage wire, respectively. Case no. 5 was presented with an ipsilateral sacroiliac luxation, which was stabilized with lag screw fixation. Case no. 13 was presented with a contralateral femoral neck fracture that was treated by femoral head and neck excision. Case no. 15 had a 12th through 13th thoracic vertebral column fracture-luxation that was stabilized with pins and methylmethacrylate. Case no. 23 had a Salter-Harris type I fracture of the contralateral distal femur that was stabilized using interfragmentary cross pins.

A hybrid fixator was used in the initial management of 21 fractures, and in four dogs and one cat the fixator was applied during revision procedures to stabilize failed previous repairs. Descriptions of the surgical approach and hybrid constructs are listed in Table 2. An open approach was used to reduce eight of the humeral fractures and 10 of the femoral fractures. A limited open approach was performed in five animals. A closed reduction technique was

used in the remaining three animals. Intraoperative fluoroscopy was utilized to assess reduction and confirm correct implant placement in all but three of the surgical procedures. In 20 fractures, an intramedullary pin was placed and articulated with the fixator. Autogenous and/or allogenic cancellous bone grafting was performed in 12 fractures.

Incomplete stretch rings were used to stabilize the distal fracture segment in 23 fractures. A one-third arch was used to stabilize the proximal fracture segment of two fractures (case no. 3 had both a proximal arch and distal stretch ring, and case no. 6 had a proximal arch). The humeral condyle was secured to a five-eighth ring in two fractures. In 15 constructs, centrally threaded full-pins and end-threaded half-pins were used as the ring fixation elements. In 11 constructs, Kirschner and/or olive wires were used as ring fixation elements.

All hybrid constructs utilized a primary lateral hybrid rod, and four constructs utilized only a lateral hybrid rod. Fourteen constructs consisted of a primary lateral hybrid rod and an articulated secondary hybrid rod. The hybrid fixators applied in the remaining six animals were more elaborate constructs utilizing additional hybrid and connecting rods.

Fourteen animals experienced complications after fixator application. The most common complication was pin and/or wire tract drainage during the convalescence period. Eleven animals developed minor pin and/or wire tract inflammation,^{3,8} which responded to improved cleaning of the pin/wire-skin interfaces and administration of oral antibiotics. Two dogs had major pin and/or wire tract inflammation.^{3,8} Case no. 25 was diagnosed with an infection of the fracture site by the referring veterinarian 1 week following surgery; however, subsequent follow-up information was not available for this dog.

Twenty-two of 24 fractures with sufficient follow-up obtained union. Time to radiographic union ranged from 25 to 280 days (mean $\pm$ SD 110 ± 69 days; median 98 days). The fixator was removed at the time radiographic union was observed in 21 animals, and the fixator was removed prior to definitive radiographic union in three animals. Partial and progressive removal of the hybrid construct was performed in eight animals. Case no. 5 jumped off a deck and refractured its humerus 1 week after confirmation of radiographic union and hybrid fixator removal. The fracture was restabilized with a type IA linear fixator, and union was achieved 166 days after the second surgery. The functional outcome in this dog was considered excellent.

Fractures in two dogs failed to achieve union, and a hybrid fixator had been applied to revise previously failed surgical repairs in both dogs. Case no. 1 had recurrent pin tract infections, and osteomyelitis developed following application of the hybrid fixator. Appropriate antibiotic therapy based on cultures and sensitivities failed to resolve the infection, and the dog had only a fair functional outcome. Case no. 11 had a chronic, infected, nonunion femoral fracture that had initially been stabilized with an intramedullary pin and cerclage wires. The fractured femur

Table 1

Clinical and Radiographic Data for 26 Animals With Humeral or Femoral Fractures Stabilized With Linear-Circular Hybrid Fixator Constructs

Case No.	Signalment*	History	Duration From Injury to Surgery (Days)	Description of Fracture†	Complications	Time to Union / Fixator Removal (Days Following Surgery)	Functional Outcome (Mos Following Surgery)
1	5-y-old, 34-kg, M German shepherd dog	Injured during training	14	Comminuted (IV) supra- and intracondylar left humeral fracture‡,§	Major pin tract inflammation	Nonunion/232	Fair (7 ^D /41 ^T),¶
2	6-y-old, 24-kg, SF Brittany spaniel	Motor vehicle accident	4	Highly comminuted (IV) distal metaphyseal-diaphyseal left femoral fracture	Minor pin tract inflammation	163/163	Excellent (6 ^D /36 ^T)
3	3-y-old, 5-kg, M domestic shorthair cat	Gunshot injury	3	Open highly comminuted (IV) right proximal metaphyseal-diaphyseal humeral fracture	None	280/280	Excellent (9 ^D /31 ^T)
4	7-y-old, 54-kg, CM Labrador retriever	Motor vehicle accident	1	Comminuted (IV) distal diaphyseal-metaphyseal and intracondylar right humeral fracture§	None	96/96	Excellent (3.5 ^D /37 ^T)
5	4-y-old, 29-kg, M Pit bull terrier	Motor vehicle accident	1	Comminuted (IV) mid- to distal diaphyseal-metaphyseal right humeral fracture	Minor pin tract inflammation; refractured 7 d after fixator removal	259/259	Excellent (8 ^D /33 ^T)
6	3-y-old, 30-kg, M Pit bull terrier	Gunshot injury	1	Open comminuted (III) proximal diaphyseal right humeral fracture	None	97/97	Excellent (3 ^D /60 ^T)
7	6-y-old, 12-kg, SF cocker spaniel	Fell down a flight of stairs	34	Comminuted (II) supra- and intracondylar left humeral fracture‡,§	None	131/131	Excellent (4.5 ^D /50 ^T)
8	3-y-old, 6-kg, CM domestic shorthair cat	Motor vehicle accident	7	Highly comminuted (IV) supra- and intracondylar left humeral fracture§	None	218/218	Fair (23 ^D)
9	6-mo-old, 9-kg, F beagle	Motor vehicle accident	1	Comminuted (II) distal metaphyseal right femoral fracture	None	27/27	Excellent (1 ^D /22 ^T)

(Continued on next page)

Table 1 (cont'd)

Clinical and Radiographic Data for 26 Animals With Humeral or Femoral Fractures Stabilized With Linear-Circular Hybrid Fixator Constructs

Case No.	Signalment*	History	Duration From Injury to Surgery (Days)	Description of Fracture†	Complications	Time to Union / Fixator Removal (Days Following Surgery)	Functional Outcome (Mos Following Surgery)
10	3-mo-old, 9-kg, F Great Dane	Motor vehicle accident	1	Transverse comminuted (II) mid- to distal diaphyseal left femoral fracture	Minor pin tract inflammation	25/11	Excellent (1 ^D /26 ^T)
11	4-y-old, 9-kg, CM Boston terrier	Motor vehicle accident	365	Infected nonunion comminuted (IV) proximal diaphyseal left femoral‡	Major pin tract inflammation	Nonunion/970	Fair (31 ^D /33 ^T)
12	3-y-old, 4.6-kg, M Chihuahua	Dog fight	1	Comminuted (I) spiral mid-diaphyseal right humeral fracture	None	49/49	Excellent (1.5 ^D /22 ^T)
13	11-mo-old, 18-kg, CM cur	Unknown	2	Comminuted (IV) distal diaphyseal-metaphyseal left humeral fracture	Minor pin tract inflammation	98/98	Good (4 ^D)
14	11-y-old, 23-kg, M bulldog	Motor vehicle accident	1	Comminuted (II) distal diaphyseal-metaphyseal left humeral fracture	Minor pin tract inflammation	126/126	Good (4 ^D /22 ^T)
15	8-mo-old, 25-kg, F Labrador retriever	Motor vehicle accident	3	Comminuted (II) oblique supracondylar left femoral fracture	Minor pin tract inflammation	37/37	Excellent (3.5 ^D /8 ^T)
16	5-y-old, 22-kg, CM English springer spaniel	Motor vehicle accident	1	Comminuted (II) supra- and intracondylar left humeral fractures§	None	87/87	Excellent (30 ^D /39 ^T)
17	4-y-old, 3-kg, SF domestic shorthair cat	Motor vehicle accident	1	Highly comminuted (IV) supra- and intracondylar left humeral fractures§	None	77/77	Excellent (6 ^D /50 ^T)
18	1-y-old, 31-kg, M mixed-breed dog	Gunshot injury	3	Open comminuted (III) proximal diaphyseal right femoral fracture	Minor pin tract inflammation	59/59	Good (3 ^D)

(Continued on next page)

Table 1 (cont'd)

Clinical and Radiographic Data for 26 Animals With Humeral or Femoral Fractures Stabilized With Linear-Circular Hybrid Fixator Constructs

Case No.	Signalment*	History	Duration From Injury to Surgery (Days)	Description of Fracture†	Complications	Time to Union / Fixator Removal (Days Following Surgery)	Functional Outcome (Mos Following Surgery)
19	4-y-old, 5-kg, CM domestic shorthair cat	Gunshot injury	3	Open comminuted (III) distal diaphyseal left humeral fracture	None	115/115	Excellent (4 ^D /18 ^T)
20	4-y-old, 5.8-kg, SF bichon frise	Motor vehicle accident	47	(0) Supracondylar distal right femoral fracture‡	None	109/109	Good (4 ^D)/Excellent (5 ^T)
21	2-y-old, 5.4-kg, M Jack Russell terrier	Motor vehicle accident	2	Comminuted (II) Salter-Harris IV supra- and intracondylar left humeral fractures§	None	105/105	Excellent (3.5 ^D /4.5 ^T)
22	1-y-old, 15-kg, M mixed-breed dog	Motor vehicle accident	Unknown	Highly comminuted (IV) right distal diaphyseal-metaphyseal femoral fracture	Minor pin tract inflammation	Follow-up not available	Unknown
23	7-mo-old, 6.4-kg, CM Jack Russell terrier	Motor vehicle accident	4	(0) Salter-Harris II left distal femoral fracture	Minor pin tract inflammation	78/78	Good (2 ^D)
24	2-y-old, 5.2-kg, CM domestic shorthair cat	Injured while jumping	20	Comminuted (II) supra- and intracondylar right femoral fracture‡,§	Minor pin tract inflammation	54/54	Good (2 ^D /12 ^T)
25	5-y-old, 43-kg, CM rottweiler	Gunshot injury	7	Open highly comminuted (IV) proximal metaphyseal-diaphyseal right femoral fracture	Surgical site infection	Follow-up not available	Unknown
26	8-y-old, 24-kg, SF Labrador retriever	Jumped from motor vehicle	1	Highly comminuted (IV) proximal metaphyseal-diaphyseal-distal metaphyseal right femoral fracture	Minor pin tract inflammation	136/136	Excellent (4.5 ^D /12 ^T)

(Continued on next page)

Table 1 (cont'd)

Clinical and Radiographic Data for 26 Animals With Humeral or Femoral Fractures Stabilized With Linear-Circular Hybrid Fixator Constructs

* M=male; SF=spayed female; CM=castrated male; F=female

† Modified Winquist-Hansen classification of fracture comminution in parentheses [see Appendix]

‡ Hybrid circular-linear fixator applied to revise previous failed surgical repair

§ Articular fracture

\ D Information obtained by direct evaluation

¶ T Information obtained by telephone contact with owner or referring veterinarian

Table 2

Details Regarding Surgery and Construct Design for 26 Animals With Humeral or Femoral Fractures Stabilized With Linear-Circular Hybrid Fixator Constructs

Case No.	Surgical Approach ^{*,†}	Internal Fixation	Position of Ring(s)	Configuration/ Diameter of Ring(s)	Fixation Elements on Ring(s) [‡]	Linear Rods [§]	Linear Fixation Elements [‡]
1	Open ^{*,†}	IM pin; [\] intracondylar lag screw	Humeral condyle	Stretch/118 mm	One 3.2-mm PPCT full-pin	1° lateral hybrid rod; 2° craniomedial hybrid rod articulated proximolaterally with 1° rod and IM pin; 3° caudomedial hybrid rod	1° rod: three 3.2-mm PPET half-pins 2° rod: one 3.2-mm PPET half-pin 3° rod: one 3.2-mm PPET half-pin
2	Open ^{*,†}	IM pin; [\] two cerclage wires	Femoral condyles	Stretch/118 mm	One 3.2-mm PPCT full-pin and one medial 3.2-mm PPET half-pin	1° lateral hybrid rod articulated with the IM pin via a carbon fiber rod; 2° craniolateral hybrid rod articulated proximolaterally with 1° rod; 3° caudomedial hybrid rod articulated proximolaterally with 1° rod	1° rod: two 3.2-mm PPET half-pins 3° rod: one 3.2-mm PPET half-pin
3	Closed [*]	IM pin [\]	Proximal metaphysis and humeral condyle	1/3 arch (proximal metaphysis); stretch (condyle)/ 66 mm	Proximal arch: two 2.5-mm PPET half-pins Distal ring: one 2.5-mm PPCT full-pin	1° lateral carbon fiber rod; 2° craniomedial hybrid rod articulated proximally with IM pin; 3° caudomedial hybrid rod; 4° cranial hybrid rod articulated craniolaterally to arch	1° rod: one 2.5-mm PPET half-pin 3° rod: one 2.5-mm PPET half-pin
4	Limited open [*]	IM pin; [\] supra- and intracondylar lag screws	Humeral condyle	Stretch/118 mm	One 3.2-mm PPCT full-pin	1° lateral hybrid rod; 2° craniomedial hybrid rod articulated proximocranially to 1° rod; 3° cranial hybrid rod articulated proximolaterally with the IM pin; 4° caudomedial hybrid rod	1° rod: one 3.2-mm PPET half-pin 3° rod: two 3.2-mm PPET half-pins 4° rod: one 3.2-mm PPET half-pin

(Continued on next page)

Table 2 (cont'd)
 Details Regarding Surgery and Construct Design for 26 Animals With Humeral or Femoral Fractures
 Stabilized With Linear-Circular Hybrid Fixator Constructs

Case No.	Surgical Approach ^{*,†}	Internal Fixation	Position of Ring(s)	Configuration/ Diameter of Ring(s)	Fixation Elements on Ring(s) [‡]	Linear Rods [§]	Linear Fixation Elements [‡]
5	Closed [*]	IM pin [\]	Humeral condyle	Stretch/118 mm	One 3.2-mm PPCT full-pin and one 3.2-mm PPET half-pin	1° lateral hybrid rod; 2° craniomedial hybrid rod articulated proximally with the IM pin; 3° cranial hybrid rod articulated craniolaterally to 1° rod	1° rod: two 3.2-mm PPET half-pins 2° rod: one 3.2-mm PPET half-pin
6	Limited open [*]	IM pin [\]	Proximal humeral metaphysis	1/3 arch/84 mm	Two 3.2-mm PPET half-pins	1° lateral hybrid rod; 2° lateral articulated carbon fiber rod articulated proximally to the IM pin and distally to 1/3 arch	1° rod: one 3.2-mm PPET half-pin 2° rod: two 3.2-mm PPET half-pins
7	Open ^{*,†}	None	Humeral condyle	Stretch/66 mm	One 3.5-mm PPCT full-pin and one 1.6-mm Kirschner wire	1° lateral hybrid rod; 2° craniomedial hybrid rod articulated proximolaterally with 1° rod via a carbon fiber rod	1° rod: three 3.2-mm PPET half-pins
8	Limited open ^{*,†}	None	Humeral condyle	Stretch/50 mm	Two 1.6-mm olive wires	1° lateral hybrid rod, titanium; 2° cranial hybrid rod, proximolateral to distomedial, titanium	1° rod: three 2.5-mm PPET half-pins 2° rod: one 2.5-mm PPET half-pin
9	Open [*]	IM pin [\]	Distal femoral metaphysis	Stretch/84 mm	Two 1.6-mm olive wires and one 1.6-mm Kirschner wire	1° lateral hybrid rod articulated with the IM pin [¶]	1° rod: one 3.2-mm NPET half-pin and one 2.4-mm NPET half-pin
10	Closed [*]	None	Distal femoral metaphysis	Stretch/84 mm	Two 1.6-mm olive wires and one 1.6-mm Kirschner wire	1° lateral hybrid rod	1° rod: three 3.2-mm PPET half-pins
11	Open [†]	IM pin [\]	Femoral condyles	Stretch/66 mm	One 4.0-mm PPCT full-pin	1° lateral hybrid rod articulated proximolaterally with the IM pin via a carbon fiber rod; 2° craniomedial hybrid rod articulated proximolaterally with 1° rod	1° rod: one 3.2-mm PPET half-pin 2° rod: two 2.4-mm NPET half-pins (Continued on next page)

Table 2 (cont'd)
 Details Regarding Surgery and Construct Design for 26 Animals With Humeral or Femoral Fractures
 Stabilized With Linear-Circular Hybrid Fixator Constructs

Case No.	Surgical Approach ^{*,†}	Internal Fixation	Position of Ring(s)	Configuration/ Diameter of Ring(s)	Fixation Elements on Ring(s) [‡]	Linear Rods [§]	Linear Fixation Elements [‡]
12	Open [*]	IM pin; [\] four cerclage wires	Humeral condyle	Stretch/66 mm	One 1.6-mm olive wire	1° lateral hybrid rod articulated proximolaterally with the IM pin [¶]	1° rod: two 2.4-mm NPET half-pins
13	Open [*]	IM pin; [\] seven cerclage wires	Humeral condyle	Stretch/84 mm	One 4.0-mm PPCT full-pin	1° lateral hybrid rod articulated proximolaterally with the IM pin; [¶] 2° craniomedial hybrid rod	1° rod: one 4.0-mm PPET half-pin and one 3.2-mm PPET half-pin 2° rod: one 4.0-mm PPET half-pin
14	Open ^{*,†}	IM pin [\]	Humeral condyle	Stretch/84 mm	One 4.0-mm PPCT full-pin	1° lateral hybrid rod articulated proximally with the IM pin; [¶] 2° craniomedial hybrid rod articulated distally; 3° craniolateral hybrid rod; 4° caudolateral hybrid rod	1° rod: one 3.2-mm PPET half-pin 2° rod: one 3.2-mm PPET half-pin 3° rod: one 3.2-mm PPET half-pin and one 3.2-mm NPET half-pin 4° rod: one 3.2-mm NPET half-pin
15	Open [*]	IM pin [\]	Femoral condyles	Stretch/118 mm	One 4.8-mm PPCT full-pin	1° lateral hybrid rod articulated proximolaterally with the IM pin [¶] via a carbon fiber rod; 2° cranial hybrid rod	1° rod: two 4.0-mm PPET half-pins 2° rod: one 2.4-mm NPET half-pin
16	Open [*]	IM pin; [\] one intracondylar lag screw	Humeral condyle	Stretch/84 mm	Six 2.4-mm NPET half-pins	1° lateral hybrid rod articulated proximally to the IM pin	1° rod: two 3.2-mm PPET half-pins
17	Open ^{*,†}	IM pin [\]	Humeral condyle	5/8 ring/35 mm	Two 1.6-mm olive wires	1° lateral rod articulated cranially; 2° lateral rod articulated caudolaterally; 3° cranial rod articulated with the IM pin	2° rod: two 1.6-mm PPET half-pins 3° rod: two 2.2-mm NPET half-pins

(Continued on next page)

Table 2 (cont'd)
 Details Regarding Surgery and Construct Design for 26 Animals With Humeral or Femoral Fractures
 Stabilized With Linear-Circular Hybrid Fixator Constructs

Case No.	Surgical Approach ^{*,†}	Internal Fixation	Position of Ring(s)	Configuration/ Diameter of Ring(s)	Fixation Elements on Ring(s) [‡]	Linear Rods [§]	Linear Fixation Elements [‡]
18	Open	IM pin [‡]	Femoral condyles	Stretch/118 mm	One 4-mm PPCT full-pin	1° lateral hybrid rod articulated proximally with the IM pin via a carbon fiber rod; 2° cranial hybrid rod articulated proximolaterally to 1° rod via a carbon fiber rod	1° rod: three 4.0-mm PPET half-pins and one 3.2-mm NPET half-pin
19	Limited open ^{*,†}	IM pin [‡]	Humeral condyle	5/8 ring/50 mm	Two 1.6-mm olive wires and one 1.0-mm Kirschner wire	1° lateral hybrid rod; 2° craniomedial hybrid rod articulated proximally to the IM pin via a carbon fiber rod	1° rod: two 2.0-mm NPET half-pins and one 2.5-mm PPET half-pin
20	Open ^{*,†}	One 1.0-mm interfragmentary Kirschner wire	Femoral condyles	Stretch/50 mm	Two 1.6-mm Kirschner wires	1° lateral hybrid rod; 2° cranial rod articulated proximally with hybrid rod	1° rod: two 2.4-mm NPET half-pins
21	Open ^{*,†}	Five 1.0-mm Kirschner wires	Humeral condyle	Stretch/50 mm	One 2.4-mm PPCT full-pin	1° lateral hybrid rod; 2° craniomedial rod articulated proximally with hybrid rod	1° rod: three 2.4-mm PPET half-pins
22	Open ^{*,†}	IM pin [‡] ; two 1.6-mm interfragmentary Kirschner wires	Femoral condyles	Stretch/84 mm	Two 1.6-mm olive wires and one 1.6-mm Kirschner wire	1° lateral hybrid rod articulated proximally with the IM pin via a titanium rod; 2° craniomedial rod articulated proximally with hybrid rod	1° rod: four 2.4-mm PPET half-pins
23	Open [*]	Two 1.6-mm and two 1.0-mm interfragmentary Kirschner wires; one intracondylar lag screw	Femoral condyles	Stretch/66 mm	Two 1.0-mm Kirschner wires	1° lateral hybrid rod; 2° craniomedial rod articulated proximally with hybrid rod	1° rod: two 2.0-mm NTS half-pins
24	Open [*]	IM pin; one 1.0-mm interfragmentary Kirschner wire	Femoral condyles	Stretch/66 mm	Two 1.6-mm olive wires	1° lateral hybrid rod; 2° cranial rod articulated proximally with hybrid rod	1° rod: two 2.0-mm NTS half-pins (Continued on next page)

Table 2 (cont'd)
 Details Regarding Surgery and Construct Design for 26 Animals With Humeral or Femoral Fractures Stabilized With Linear-Circular Hybrid Fixator Constructs

Case No.	Surgical Approach ^{*†}	Internal Fixation	Position of Ring(s)	Configuration/ Diameter of Ring(s)	Fixation Elements on Ring(s) [‡]	Linear Rods [§]	Linear Fixation Elements [‡]
25	Open [*]	IM pin\	Femoral condyles	Stretch/118 mm	One 4.0-mm PPCT full-pin	1° lateral hybrid rod articulated proximal to the IM pin via carbon fiber rod; 2° craniomedial rod articulated proximally with 1° rod	1° rod: three 3.2-mm PPET half-pins
26	Limited open [†]	IM pin;\ three cerclage wires	Femoral condyles	Stretch/118 mm	One 3.2-mm PPCT full-pin and one 3.2-mm PPET half-pin	1° lateral hybrid rod; 2° craniomedial hybrid rod articulated proximally with 1° rod and the IM pin	1° rod: three 3.2-mm PPET half-pins 2° rod: one 3.2-mm PPET half-pin

^{*} Fluoroscopy used during surgery
[†] Bone graft

[‡] PPCT=positive-profile centrally threaded; PPET=positive-profile end-threaded; NTS=nonthreaded Steinmann
[§] 1°=primary; 2°=secondary; 3°=tertiary; 4°=quaternary

\ Intramedullary (IM) pin articulated with fixator

¶ Protruding segment of intramedullary (IM) pin bent to simplify articulation with fixator

was approximately 30% shorter than the contralateral femur and had extreme diffuse osteopenia. At the time of revision surgery and application of a hybrid fixator, the remaining implants were removed, the nonunion site was débrided, and an autogenous cancellous bone graft was placed in the fracture site. Postoperatively, the fixation pins in the proximal femur developed purulent drainage with associated radiolucency. Sixty-nine days after application of the hybrid fixator, progression toward fracture union was not evident, and further revision was advised. The owner declined further treatment, and the referring veterinarian finally removed the frame 970 days after application, despite persistent radiographic nonunion. The dog had improved use of the limb following fixator removal, and the owners assessed the dog's limb function as fair.

Final direct evaluation of limb function was performed between 1 and 31 months after the application of the hybrid fixator (mean $\pm$ SD 7.0 $\pm$ 8.5 months; median 4.0 months). Telephone interviews with the owners assessing their dog's limb function were conducted between 4.5 and 60.0 months (mean $\pm$ SD 27.4 $\pm$ 15.6 months; median 26.0 months). Long-term functional outcome was assessed by owners to be excellent in 16 animals and good in five animals. Limb function in three animals (including the two dogs in which the fracture did not achieve union) was assessed as fair. The third animal assessed as having fair limb function was the cat (case no. 8) that had sustained a traumatic ipsilateral

scapulohumeral luxation subsequent to stabilization of its humeral fracture. Follow-up information was unavailable for two dogs.

Results of the Cox regression analysis and univariate analysis are shown in Table 3. The odds of union in animals with modified Winquest-Hansen scores III or IV were 0.26 times those in animals with scores 0, I, or II (HR 0.26; 95% CI 0.09 to 0.72; $P=0.01$). In the multivariable analysis, the variables for bone, complication, graft, and reduction were not significantly associated with time to union ($P>0.10$) and were removed from the model. Modified Winquest-Hansen scores, revision surgery, and age were retained in the final modeling process [Table 3]. The odds of union in animals with modified Winquest-Hansen scores of III or IV were 0.16 times those in animals with scores of 0, I, or II (HR 0.16; 95% CI 0.05 to 0.49; $P<0.01$) after controlling for revision surgery and age. Animals with low scores were used as the reference category (odds ratio [OR] 1.0, the null value). An OR of 0.16 indicates that the odds of union in dogs with high scores was 0.16 times that in dogs with low scores. In other words, the odds of union was 6.25 ($1.0/0.16 = 6.25$) times higher in dogs with low scores compared to dogs with high scores. The odds of union in animals having revision surgery were 0.20 times the odds of union in animals with hybrid fixators used to initially stabilize fractures (HR 0.20; 95% CI 0.04 to 0.92; $P=0.03$).

Table 3

Cox Proportional Hazard Ratios and 95% Confidence Intervals for Time to Union in 26 Animals With Humeral or Femoral Fractures Stabilized With Linear-Circular Hybrid Fixator Constructs (Multivariable Analysis)

Variable	HR*	95% CI†	P Value
Winquest score			
0, I, II	1.00	Reference	NA‡
III, IV	0.16	0.05 to 0.49	<0.01
Revision surgery			
No	1.00	Reference	NA
Yes	0.20	0.04 to 0.92	0.03
Age (mos)			
3 to 60	1.00	Reference	NA
61 to 132	0.56	0.18 to 1.72	0.31

* HR=hazard ratio

† CI=confidence interval

‡ NA=not available

Discussion

The use of hybrid fixators to stabilize fractures of the crus and antebrachium has been described; however, limited information is available describing the use of hybrid constructs for proximal extremity fractures.^{9,15} This case series validates the efficacy of hybrid fixators for the stabilization of humeral and femoral fractures. The circular components of hybrid fixators are particularly advantageous for stabilizing fractures with short, juxta-articular fracture segments.^{9,15} Fractures in this case series involved the proximal or distal metaphysis-diaphysis, and the limited bone stock available in these juxta-articular fracture segments would have made application of a bone plate or interlocking nail difficult.

In 11 animals, multiple points of fixation were obtained in short bone segments by using small-diameter fixation wires. In this case series, wires were used to secure juxta-articular humeral and femoral segments in smaller dogs (mean $\pm$ SD body weight 8.5 ± 3.5 kg) and in four of five cats. Biomechanical studies have suggested that wires should be placed at 90° to one another in order to achieve maximum construct stability and prevent translocation of the secured bone segment.^{17,18} This practice is often limited because of anatomical constraints.⁸ Olive wires were utilized in eight fractures to improve bending stiffness and prevent translocation of the secured bone segment. In five fractures, olive wires were used to achieve interfragmentary compression.¹⁹ More than two wires were used in four fractures.

Full- or half-pins were used as fixation elements attached to ring components in 16 animals. Both a full-pin and wire were used in one fracture. The attending surgeon made the decision regarding whether wires or pins were used for ring fixation elements, based on the weight of the animal, fracture configuration, and size of bone segment requiring stabilization. Fixation pins were typically used in larger dogs. Weight range for dogs with humeral fractures was 5.0 to 54.0 kg (mean $\pm$ SD 22.0 ± 13.9 kg), and weight range for dogs with femoral fractures was 24.0 to 43.0 kg (mean $\pm$ SD 29.4 ± 8.1 kg).

Both a full-pin and Kirschner wire were utilized as ring fixation elements to secure the juxta-articular fracture segment in case no. 7. Mixing fixation elements of different stiffness can potentiate implant loosening and is discouraged.^{7,17} The full-pin was placed through the humeral condyle in this dog, but the supracondylar region was too small to accommodate a second full- or half-pin. Although a Kirschner wire was used to provide a second point of fixation in the juxta-articular fracture segment secured by the ring in this dog, implant complications did not develop.

In 24 of the 26 fractures described, incomplete rings were used to stabilize the distal fracture segments, and linear components were used to stabilize the proximal fracture segments. The open ends of the stretch rings were directed caudally in all femoral fractures, allowing full range of motion in the stifle. Rings were positioned with the open portion of the ring directed cranially in nine of 14 humeral fractures, allowing for full range of motion in the elbow. In

four humeral fractures, the rings were positioned with the open portion positioned caudally, which simplified the placement of secondary hybrid rods. Although full flexion of the elbow was restricted by positioning the open portion of the stretch ring caudally, ambulation was not impeded. Two animals had proximal humeral metaphyseal fractures, which were stabilized using one-third arches placed laterally and secured to linear components distally. The one-third arch ring allowed placement of multiple divergent half-pins to stabilize the proximal juxta-articular fracture segments.

An open surgical approach was used in the majority of the fractures to facilitate fracture reduction, internal implant placement, and bone graft placement. A limited open approach was used in five fractures, and a closed approach was used in three fractures. Intraoperative fluoroscopy was utilized to ensure proper implant placement and fracture reduction with all closed and limited open procedures and all but three open procedures. Eight fractures had articular components, and assessment of anatomical reconstruction of the articular surface was facilitated by intraoperative fluoroscopy in seven of these animals. In six animals, opposing olive wires were used to provide primary or adjunctive stabilization of the articular component of the fracture.

In all but three fractures, internal fixation was combined with hybrid fixators. Six fractures were anatomically reduced, and six fractures were partially reduced to achieve load sharing of the fracture. Hybrid fixators were able to provide buttress fixation to highly comminuted fractures, and 14 fractures were stabilized without attempting anatomical fracture reconstruction. Fourteen animals had fractures with modified Winquest-Hansen scores of III or IV, with 10 of these animals having good or excellent outcomes. However, the median time to union was 50 days longer for fractures with higher comminution scores compared to those with a score of 0, I, or II [Figure 3].

External fixation is advantageous for the treatment of open or contaminated fractures for several reasons: reduction and fixation can be applied with limited iatrogenic trauma; stabilization can be achieved without placing permanent implants at the fracture site; and the fixation elements can be removed once the fracture has achieved union.^{21,22} Hybrid fixators were successfully used in four of five contaminated fractures. Five cases were presented with open fractures as the result of gunshot injuries; functional outcome was considered excellent in three of these cases and good in one case. Follow-up information was unavailable for the final case.

Similar to other reports describing the use of circular and hybrid fixators for fracture management in dogs and cats, pin and wire tract inflammation was the most common postoperative complication affecting animals in this case series.^{7-9,15} In two previous case series describing the use of circular fixators to stabilize antebrachial and crural fractures in dogs and cats, the incidence rates of pin and/or wire tract inflammation were 88% and 100%.^{7,8} Rings securing bone segments with prominent adjacent muscle groups in locations such as the proximal radius or tibia were particularly problematic.⁸ The linear components of a hybrid fixator

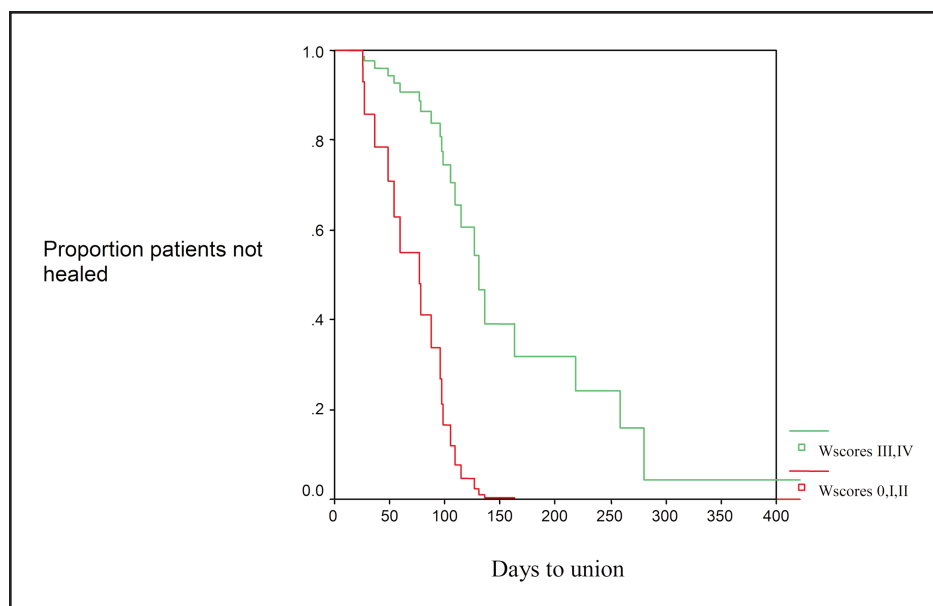


Figure 3—Time to union (adjusted for revision surgery and age) in animals with modified Winquest-Hansen comminution scores of 0, I, or II versus III or IV.

system allow the surgeon to place unilateral half-pins in defined, safe corridors, thereby avoiding the placement of fixation elements through large muscle groups.^{9,23,24} The humerus and femur are surrounded by large muscle groups, yet only half of the animals in this case series developed pin and/or wire tract inflammation. Half-pins were inserted through specifically defined, safe corridors that limited muscle impalement.^{23,24} In 11 of the 13 animals, pin and/or wire tract inflammation was minor and resolved with improved pin and/or wire tract care and antibiotic administration.^{3,7} Due to the retrospective nature of this study, specifics were not consistently available regarding which particular pin(s) and/or wires(s) were involved. Two dogs in which hybrid fixators were utilized to revise previous unsuccessful fracture repairs had major wire and/or pin inflammation that did not respond to local and systemic therapy.

Time to union and fixator removal ranged from 25 to 280 days (mean $\pm$ SD 110 $\pm$ 69 days), and it varied depending on the age of the animal, fracture comminution score, and whether a hybrid fixator was placed to revise a previously failed repair. Although no statistical association was found between age and time to union, 10 animals spent >110 days in the fixator, and all were >3 years of age (range 3 to 11 years). Fourteen animals spent <110 days in the fixator, and all were <7 years of age (range 3 months to 7 years). Seven of these 14 animals were <1 year of age. Animals with highly comminuted fractures (modified Winquest-Hansen scores of III and IV) had significantly longer times to union than animals with less complex fractures (modified Winquest-Hansen scores of 0, I, and II). Prolonged time to union was also significantly associated with application of the hybrid fixator during revision of a previous unsuccessful repair. Animals undergoing revision surgery were five times more likely to have a nonunion than animals that had a hybrid fixator applied to initially stabilize the fracture. Although hybrid fixators were used successfully

to revise fractures in three animals that had previous repairs, two of five animals having revision surgeries failed to achieve union. Both of these dogs experienced major pin tract complication and had only fair functional outcomes.

The retrospective nature of this study prevented a standardization of procedures and examinations. Cases were collected from three referral institutions; surgical procedures were performed by surgeons with varying levels of experience; frame configurations varied widely, depending on the fracture and the surgeon performing the procedure; and direct, long-term follow-up evaluations were not consistent. Furthermore, the majority of the follow-up information was obtained via telephone interviews with owners. While this is a subjective method of examination, the success of the procedure is, ultimately, determined by the owner's perception of the pet's limb function. Despite these limitations, the overall positive results described in this case series substantiate previous case studies that demonstrate the versatility and effectiveness of the hybrid system.

Conclusion

Hybrid fixators are useful constructs for stabilization of humeral and femoral fractures, particularly fractures with short, juxta-articular fracture segments. Hybrid constructs proved effective for the management of open and/or highly comminuted fractures, although fractures with modified Winquest-Hansen comminution scores of III or IV can be expected to take longer to heal. Hybrid fixators can be used to revise previously failed surgeries; however, this case series showed that revision surgeries were associated with longer convalescence periods and poorer outcomes. While pin and/or wire tract inflammation can be expected, drainage can generally be controlled with oral administration of antimicrobials and vigilant cleaning of the pin/wire skin interfaces.

Footnotes

^a IMEX Hybrid ESF System; IMEX Veterinary, Inc., Longview, TX 75604

^b SK ESF System; IMEX Veterinary, Inc., Longview, TX 75604

^c Cefazolin; Orchid Healthcare, Weston, FL 33326

Acknowledgments

The authors acknowledge the clinical contributions of Drs. Ursula Krotscheck, Stephen Royals, Jennifer Fick, Kara Mattern, Colin Sereda, and Carl Jehn.

References

1. Elkins AD, Morandi M, Zembo M. Distraction osteogenesis in the dog using the Ilizarov external ring fixator. *J Am Anim Hosp Assoc* 1993;29:419-426.
2. Ehrhart N, Eurell JAC, Tommasini M, *et al.* Effect of cisplatin on bone transport osteogenesis in dogs. *Am J Vet Res* 2002;63:703-711.
3. Lewis DD, Radasch RM, Beale BS, *et al.* Initial clinical experience with the IMEX circular external skeletal fixation system. Part II: use in bone lengthening and correction of angular and rotational deformities. *Vet Comp Orthop Traumatol* 1999;12:118-127.
4. Marcellin-Little DJ, Ferretti A, Roe SC, *et al.* Hinged Ilizarov external fixation for correction of antebrachial deformities. *Vet Surg* 1998;27:231-245.
5. Welch RD, Lewis DD. Distraction osteogenesis. *Vet Clin North Am Small Anim Pract* 1999;29:1187-1205.
6. Stallings JT, Lewis DD, Welch RD, *et al.* An introduction to distraction osteogenesis and the principles of the Ilizarov method. *Vet Comp Orthop Traumatol* 1998;11:59-67.
7. Lewis DD, Radasch RM, Beale BS, *et al.* Initial clinical experience with the IMEX circular external skeletal fixation system. Part I: use in fractures and arthrodeses. *Vet Comp Orthop Traumatol* 1999;12:108-117.
8. Anderson GM, Lewis DD, Radasch RM, *et al.* Circular external skeletal fixation stabilization of antebrachial and crural fractures in 25 dogs. *J Am Anim Hosp Assoc* 2003;39:479-498.
9. Farese JP, Lewis DD, Cross AR, *et al.* Use of IMEX SK-circular external fixator hybrid constructs for fracture stabilization in dogs and cats. *J Am Anim Hosp Assoc* 2002;38:279-289.
10. Lewis DD, Cross AR, Carmichael S, *et al.* Recent advances in external skeletal fixation. *J Small Anim Pract* 2001;42:103-112.
11. Marcellin-Little DJ. Fracture treatment with circular external fixation. *Vet Clin North Am Small Anim Pract* 1999;29:1153-1170.
12. Ilizarov GA. The tension-stress effect on the genesis and growth of tissues. *Clin Ortho* 1989;38:249-281.
13. Goodship AE, Kenwright J. The influence of induced micromovement upon the healing of experimental tibial fractures. *J Bone Joint Surg [Br]* 1985;67:650-655.
14. Kenwright J, Richardson JB, Cunningham JL, *et al.* Axial movement and tibial fractures. A controlled randomised trial of treatment. *J Bone Joint Surg [Br]* 1991;73:654-659.
15. Clarke SP, Carmichael S. Treatment of distal diaphyseal fractures using hybrid external skeletal fixation in three dogs. *J Small Anim Pract* 2006;47:98-103.
16. Fox SM, Bray JC, Guerin SR, *et al.* Antebrachial deformities in the dog: treatment with external fixation. *J Small Anim Pract* 1995;36:315-320.
17. Lewis DD, Bronson DG, Cross AR, *et al.* Axial characteristics of circular external skeletal fixator single ring constructs. *Vet Surg* 2001;30:386-394.
18. Orbay GL, Frankel VH, Kummer FJ. The effect of wire configuration on the stability of the Ilizarov external fixator. *Clin Orthop* 1992;279:299-302.
19. Cross AR, Lewis DD, Murphy ST, *et al.* Effects of ring diameter and wire tension on the axial biomechanics of four-ring circular external skeletal fixator constructs. *Am J Vet Res* 2001;62:1025-1030.
20. Aron DN, Foutz TL, Keller WG, *et al.* Experimental and clinical experience with an IM pin external skeletal fixator tie-in configuration. *Vet Comp Orthop Traumatol* 1991;4:86-94.
21. Lincoln JD. Treatment of open, delayed union, and non-union fractures with external skeletal fixation. *Vet Clin North Am Small Anim Pract* 1992;22:195-207.
22. Ness MG. Treatment of inherently unstable open infected fractures by open wound management and external skeletal fixation. *J Small Anim Pract* 2006;47:83-88.
23. Marti JM, Miller A. Delimitation of safe corridors for the insertion of external fixator pins in the dog I: hindlimb. *J Small Anim Pract* 1994;35:16-23.
24. Marti JM, Miller A. Delimitation of safe corridors for the insertion of external fixator pins in the dog II: forelimb. *J Small Anim Pract* 1994;35:78-85.