Movora Education

Move FORWARD

Continuing Education for Your Unique Journey

Whether learning a new procedure or keeping your techniques current, Movora Education is here to help you keep moving forward.

100+ Workshops Annually
From simple Fracture Repair to complex Total Joint Replacement.

State-of-the-Art Training Facilities
Continue your education at well-equipped Movora Education Centers and partner venues.

Online Courses for All Skill Levels
Learn wherever you are at your own pace.

SCAN HERE

REGISTRATION OPEN

Find your pathway online at education.movora.com

BioMedtrix® | IMEX® Veterinary, Inc. | KYON | NGD New Generation Devices | VOI Veterinary Orthopedic Implants

Received: 23 March 2022 | Revised: 12 September 2022 | Accepted: 17 October 2022

DOI: 10.1111/vsu.13911

CLINICAL RESEARCH

WILEY

Linear external skeletal fixation applied in minimally invasive fashion for stabilization of nonarticular tibial fractures in dogs and cats

Alec H. Sherman DVM[1] | Karl H. Kraus DVM, MS, DACVS[1] | Danielle Watt DVM[1] | Lingnan Yuan BS[2] | Jonathan P. Mochel DVM, MS, PhD, DECVPT, AAVPT Fellow[2]

[1]Department of Medicine and Surgery, College of Veterinary Medicine, Hixson-Lied Small Animal Hospital, Iowa State University, Ames, Iowa, USA

[2]Department of Biomedical Sciences, College of Veterinary Medicine, Iowa State University, Ames, Iowa, USA

Correspondence
Alec H. Sherman, Department of Medicine and Surgery, College of Veterinary Medicine, Hixson-Lied Small Animal Hospital, Iowa State University, Ames, IA 50010, USA.
Email: alechsherman@gmail.com

Abstract

Objective: The objective of this study was to evaluate the use of linear external skeletal fixation (ESF) applied using minimally invasive techniques in dogs and cats.

Study design: Retrospective study.

Animals: Forty-nine dogs and 6 cats.

Methods: Medical records of cases with nonarticular tibial fractures, repaired using linear ESF at a single academic institution between July 2010 and 2020, were reviewed. All records of cases that had nonarticular tibial fractures repaired using linear ESF were included. Information was collected regarding signalment, surgical procedures performed, perioperative care, radiographic evaluation, and postoperative complications.

Results: Intraoperative imaging was used in 40/55 (72%) of cases. Tibal plateau angle (TPA), tibial mechanical medial proximal and distal tibial angles (mMPTA and mMDTA, respectively) were not affected by intraoperative imaging ($P = .344$, $P = .687$, $P = .418$). A total of 22 (40%) complications occurred. Of these, 18 were considered minor and 4 were considered major. Open fractures had more major complications than closed fractures ($P = .019$). All fractures reached radiographic union of the fracture. The mean ± SD time to external fixator removal was 71 ± 48 days.

Conclusion: Linear ESF applied using minimally invasive techniques with or without intraoperative imaging was an effective treatment for nonarticular tibial fractures.

Clinical significance: Closed application of linear ESF should be considered as a minimally invasive option for stabilizing nonarticular tibial fractures.

1 | INTRODUCTION

Fractures of the tibia are relatively common in dogs and cats, and account for 10%-20% of all fractures.[1] Multiple methods of tibia fracture fixation have been described including open reduction and internal fixation as well as minimally invasive options.[2–7] Open techniques allow for fragment observation and reduction via direct manipulation; however, they have been associated with compromise to the blood supply, which may inhibit bone healing and increase complications.[3–5,8] Minimally invasive techniques have recently gained popularity utilizing biological osteosynthesis to improve clinical outcomes.[4,9–12]

External skeletal fixation (ESF) can be applied using minimally invasive techniques and is commonly used for tibial fracture fixation.[3,5,13–16] Reported advantages of ESF include ease of placement and removal, adjustability of frames, accessibility for open wound management, and reduced cost of placement.[17,18] The principles of minimally invasive fracture reduction have long been employed with ESF, and are especially well suited for fractures of the tibia.[19,20]

Despite the benefits of ESF for minimally invasive osteosynthesis, its use for this purpose may also lead to complications associated with interference with soft tissues, more demanding postoperative care, and pin loosening.[1] In a recent retrospective study by Beever et al.[19] evaluating postoperative complications associated with ESF in dogs, a complication rate of 69% was reported. However, the region of ESF placement was associated with complications and the tibia was reported to have the lowest complication rate (41%) and the complications were mostly minor.

Many substantive studies have described the use of ESF for the treatment of tibial fractures; however, there are no large studies evaluating the use of linear ESF applied using minimally invasive techniques and evaluating postoperative tibial alignment.[3,5,13–16] No study has evaluated the utility of intraoperative imaging on tibial alignment. The objective of this study was to evaluate the use of linear ESF applied using minimally invasive techniques with and without the use of intraoperative imaging in dogs and cats. We hypothesized that the use of linear ESF applied using minimally invasive techniques would allow for restoration of alignment and allow bone healing with few complications. We also hypothesized that the use of intraoperative imaging would improve alignment.

2 | MATERIALS AND METHODS

Medical records of cases with nonarticular tibial fractures stabilized using linear ESF at a single academic institution (Iowa State Lloyd Veterinary Medical Center) between July 2010 and 2020 were reviewed. All records of dogs and cats that had nonarticular tibial fractures repaired using linear ESF were included. Cases with incomplete medical records (eg, missing surgery report, preoperative and/or postoperative radiographs) were excluded. Records with data until removal of the ESF or final evaluation after removal were considered complete. Data obtained from the medical records included signalment, location of the fracture, fracture type, surgical approach, fixator type (I-III), external fixator system used, diameter/material of connecting bar, diameter of pins, number of proximal and distal pins, surgery time, use of intraoperative imaging, additional treatments/adjustments, days to first follow up, days to removal, radiographic evaluation, complications, and clinical outcome.

The technique used for reduction in the majority of fractures was a modification of the hanging limb technique described previously.[25] The animal was placed on the surgical table with the distal limb secured directly under a hook in the operating room ceiling. The table could be raised and lowered with positioners so that the limb could be seen as being held in a straight line from the ceiling to the operating room table. The limb was aseptically prepared so the distal limb could be grasped during surgery. Care was taken to prevent medial-to-lateral angulation and rotational malalignment. The table was lowered so that approximately 50% of the animal's caudal weight was carried by the limb, thus placing tension and traction on the limb. The most proximal and distal fixation pins, were placed first and a connecting bar, typically the medial, was secured to these first pins. Pins were applied in the medial to lateral plane and as perpendicular to the long axis of the limb as possible. The limb alignment was confirmed or adjusted in a specific order: Translation, length, angulation in the medial to lateral plane, torsional alignment, angulation in the cranial to caudal plane. Translation and length were most often achieved with the hanging limb under tension. After the proximal and distal fixation pins with connecting bars were applied, angulation in the medial to lateral plane was adjusted and confirmed. Intraoperative images were obtained to confirm alignment, as alignment in this plane was considered to be the most critical (Figure 1). The clamps were tightened, and an additional connecting rod applied if type II fixators were employed. At this point the operating table was raised so that the stifle and tarsus were in approximately 90° of flexion. Torsional alignment was confirmed or corrected so that the joints were in one plane. The table was then lowered and alignment in the cranial to caudal plane was confirmed or adjusted. In some cases, this required manually rotating the proximal and/or distal bone segments. A large-gauge suture or

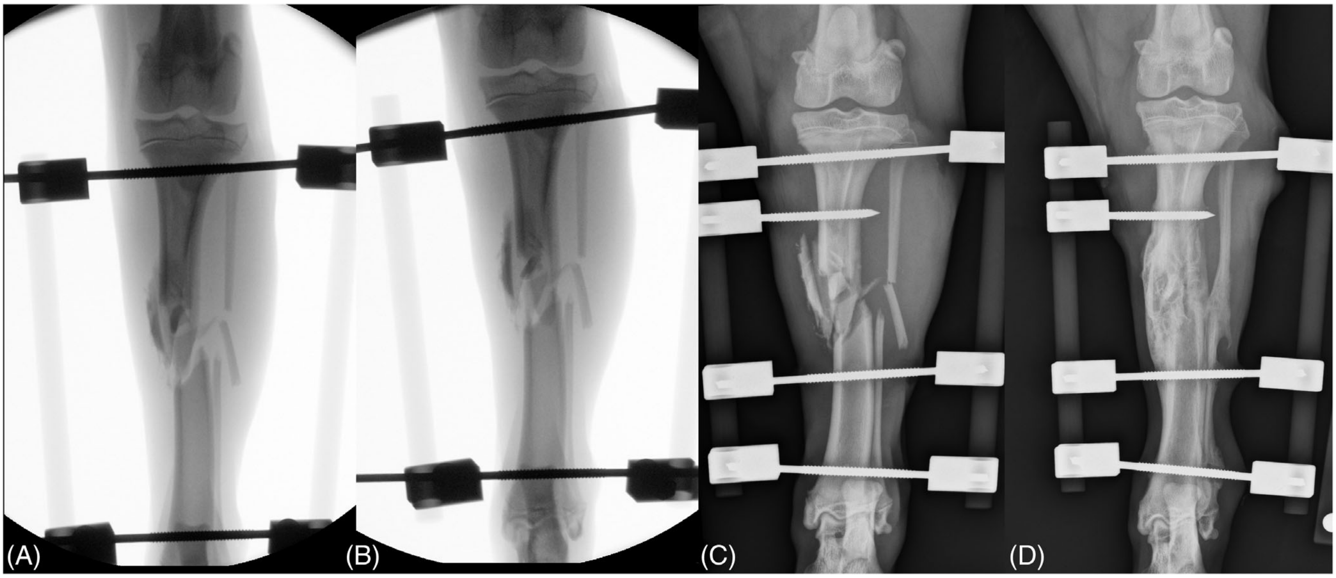

FIGURE 1 Intraoperative images (A, B) and radiographs (C, D) of a 5 month old 20 kg golden retriever that was admitted with a comminuted diaphyseal tibial fracture. Intraoperative image after initial proximal and distal fixation pin placement showing malalignment (A). Intraoperative image after manipulation of the proximal and distal fixation pins showing improved alignment (B). Immediate postoperative radiographs showing the addition of proximal and distal fixation elements (C). Fifty-one day postoperative radiograph showing complete union of the fracture (D).

umbilical tape was sometimes placed caudal to the limb and secured to the medial and lateral connecting rods to assist in sagittal plane alignment of the proximal or distal tibial segments. Alignment in the sagittal plane was considered important, but least critical.

Radiographic evaluation was performed on final radiographs prior to implant removal. Pin loosening at the time of fixator removal was evaluated using a modified Yang's scoring system.[21] Pin–bone interface was graded from 0 to 2 points. Each pin was individually graded and the total number of loose pins was reported.

Radiographic union was defined as the presence of a bridging callus of at least 3 of 4 cortices on 2 orthogonal projections. Tibial mechanical medial proximal and distal tibial angles (mMPTA and mMDTA, respectively) were measured on follow-up radiographs as described by Dismukes et al.[22] Tibial valgus was computed as ([mMPTA + mMDTA] − 180).[4] Postoperative TPA was measured on the lateral projection using the method described by Dismukes et al.[23] Rotational alignment was subjectively described as previously described by Guiot et al.[4] Alignment was considered anatomic when superposition of the caudal edges of the medial and lateral tibial plateaus as well as concentric projection of the talar trochlea ridges were simultaneously seen on lateral radiographs. Conversely, gross metatarsal angulations away from the limb sagittal plane was considered as unacceptable tibial rotational malalignment.

Complications were described as major or minor based on criteria proposed by Cook et al.[24] A major complication was defined as a complication or associated morbidity that requires further treatment based on current standards of care including both surgical and medical treatment. Minor complications were complications that did not require additional surgical or medical treatment to resolve. Clinical outcome was described as full, acceptable, or unacceptable, based on a review of physical exam performed at linear ESF removal. Full clinical outcome was defined as no apparent lameness or pain at fixator removal. Acceptable clinical outcome was defined as cases that had functional limb use with mild weight bearing lameness noted on physical exam. An unacceptable clinical outcome was defined as any case that had a toe-touching or non–weight-bearing lameness at a walk.

Differences between proportions of complications of the various study groups (use of c-arm and open fracture) were analyzed using χ^2 statistics. Due to the low number of cats ($n = 6$) in this study, comparative statistics between species would be of very low power with a high probability of type II statistical errors so species were combined. For continuous variables, differences between study groups for dependent variables (1) angles (mMPTA, mMPTA, mMDTA, Valgus and TPA) and (2) surgery time were analyzed using either *t*-tests or Wilcoxon sum rank tests after verification of normality using the Shapiro-Wilk test. *P*-values < .05 were considered as statistically significant. Corrections for multiple comparisons were performed using the Benjamini-Hochberg method. All analyses were conducted in R 4.0.3.

3 | RESULTS

A total of 75 cases were evaluated. Fifty-five cases met the inclusion criteria. Forty-nine out of 55 (89%) cases were dogs and 6 of 55 (11%) cases were cats. The mean age was 2.2 years (range 0.1-14 years). The mean weight was 19.3 kg (range 3.4-41.8 kg). Fourteen of 49 dogs were intact females, 13 of 49 were spayed females, 10 of 49 were castrated males, and 12 of 49 were intact males. Dog breeds represented included mixed breed ($n = 9$), German shepherd ($n = 8$), Labrador retriever ($n = 5$), Border collie ($n = 4$), Australian shepherd ($n = 3$), boxer ($n = 3$), American Staffordshire Terrier ($n = 2$), golden retriever ($n = 2$), great Pyrenees ($n = 2$), greyhound ($n = 2$), blue heeler ($n = 1$), bluetick hound ($n = 1$), cavalier King Charles spaniel ($n = 1$), corgi ($n = 1$), Drahthaar ($n = 1$), goldendoodle ($n = 1$), mastiff ($n = 1$), miniature schnauzer ($n = 1$), standard poodle ($n = 1$). Five out of 6 cats were castrated males and 1 of 6 cats was a spayed female. Cat breeds represented included domestic shorthair ($n = 4$) and domestic longhair ($n = 2$).

All fractures were traumatic. Fifteen of the fractures (27%) were considered open. Of the open fractures, 5/15 were Gustillo-Anderson type 1, 7/15 were Gustillo-Anderson type 2, and 3/15 were Gustillo-Anderson type 3a. Twenty-five fractures (45%) were comminuted, 22/55 (40%) of fractures were considered long oblique or spiral, 5/55 (10%) fractures were transverse and 3/55 (5%) of fractures were short oblique. Forty-nine fractures (89%) were diaphyseal, 4/55 (7%) of fractures included the distal metaphysis, and 2/55 (4%) of fractures included the proximal metaphysis.

3.1 | Operative data

Forty-nine fractures (89%) were repaired without a surgical approach to the fracture site. In the remaining 6/55 (11%) fractures a small surgical approach to the fracture for either reduction or placement of bone graft was utilized. Forty-nine fractures (89%) were treated using a hanging-limb technique.[25] The remainder were positioned in lateral recumbency with the affected leg up. The median total surgery time was 80 min (range 21-330 min). Intraoperative imaging using a c-arm (Koninklijke Philips NV, Amsterdam, Netherlands) was used in 40 of 55 (72%) cases. The median total surgical time without the use of intraoperative imaging was 100 min (range 37-285). The median total surgical time with the use of intraoperative imaging was 74 min (range 21-330 min). There was a difference in surgical time between groups ($P = .046$). All cases were overseen by a boarded American College of Veterinary Surgeons (ACVS) diplomate; however, the role of primary surgeon could not be determined from the surgery report.

A type IIb external fixator was used in 42 of 55 (76%) cases, whereas a type I was used in 12/55 (22%) and a type III in 1 of 55 (2%).[26] The SK External Skeletal Fixator System (IMEX Veterinary, Longview, Texas) was used in 16 of 55 (29%) cases and the Securos external skeletal fixator system (Securos, Fiskdale, Massachusetts) was used in 39 of 55 (71%) cases. Fixation pins chosen were based on previously described guidelines for pin diameter and surgeon experience.[27] The fixator systems including connecting rod diameter and clamps chosen were the largest that accommodated the fixation pins.

The median total number of pins was 5 (range 4-6). Twenty-six (47%) cases had 4 total pins, 10 of 55 (18%) cases had 5 total pins and 19 of 55 (35%) of cases had 6 total pins. Fourteen (25%) cases had no proximal full pins placed, 40 of 55 (73%) cases had 1 proximal full pin placed and 1 of 55 (2%) cases had 2 proximal full pins placed. Fourteen (25%) cases had no full pins placed distally, 31 of 55 (56%) cases had 1 full distal pin, and 10 of 55 (18%) cases had 2 distal full pins. Two (4%) cases had no proximal half pins, 13 or 55 (24%) cases had 1 proximal half pin, 36 of 55 (65%) cases had 2 proximal half pins, 3 of 55 (5%) cases had 3 proximal half pins and 1 of 55 (2%) cases had 4 proximal half pins. Ten (18%) cases had no distal half pins, 14 of 55 (25%) cases had 1 distal half pin, 30 of 55 (55%) cases had 2 distal half pins, and 1 of 55 (2%) cases had 3 distal half pins.

3.2 | Postoperative data

Radiographic evidence of pin loosening was seen in 10 of 55 (18%) cases. Six of 10 cases had evidence of proximal pin loosening and 4 of 10 cases had evidence of distal pin loosening. Radiographic pin loosening did not differ between proximal and distal pins ($P = .74$). The mean ± SD mMPTA was 95.3 ± 3.6° (range 86.6-103.2°) in dogs. The mean ± SD mMDTA was 95.2 ± 3.9° (range 84.5-103.9°) in dogs. Postoperative mMPTA and mMDTA were within the 95% confidence interval reported for normal dogs.[22] The mean ± SD TPA of 19.1 ± 6.8° (range 1.8-32.4°) was outside the reference range in normal dogs.[23] The mean ± SD valgus was 10.4 ± 7° (range −19.1 to 27.1°) in dogs. The mean ± SD mMPTA was 93.1 ± 3.9° (range 88.6-98.0°) in cats. The mean ± SD mMDTA was 95.5 ± 11.6° (range 72.3-103.8°) in cats. Postoperative mMPTA and mMDTA were similar to reported values in cats.[28] The mean ± SD TPA of 15.1 ± 5.0° (range 10-23.4°) was less than previously reported values in cats.[28,29] The mean ± SD valgus was 10.4 ± 7°

TABLE 1 Measurements (means ± SDs) of tibial alignment with and without intraoperative imaging

Alignment	Intraop. imaging (n = 40)	No intraop. imaging (n = 15)	P value
mMPTA	95.3 ± 3.9°	94.7 ± 3.1°	.687
mMDTA	95.4 ± 5.3°	94.9 ± 4.6°	.418
TPA	18.1 ± 6.5°	20.0 ± 7.4°	.344

(range −19.1 to 17.9°) in cats. Postoperative rotational alignment was subjectively described as anatomic in all cases. The use of intraoperative imaging had no effect on measures of fracture alignment (Table 1).

Twenty-two of 55 (40%) cases had complications. Of these, 18 of 22 were considered minor and 4 of 22 were considered major. All minor complications were associated with pin-tract morbidity and included swelling, erythema, and discharge from the pin tract. In 14 of 18 cases, swelling, erythema, and discharge were described around the proximal pin, specifically on the lateral aspect. All minor complications resolved with routine cleaning of the pin tracts and after fixator removal. The 4 major complications included failure of the external fixator apparatus (n = 1), osteomyelitis requiring antibiotic therapy and fixator revision (n = 1), sequestrum formation requiring surgical excision and bone grafting (n = 1), and refracture of the distal tibia 5 days post fixator removal (n = 1). Open fractures had a higher major complication rate than closed fractures (P = .019). There were no differences in total complications or minor complications between open and closed fractures (P = .064, P = .794). The median time to complication occurring after surgery was 28 days (range 5-88 days). Total complications, major complications and minor complications were not influenced by the use of intraoperative imaging (P = 1.000, P = .583, P = .782).

Radiographic union was achieved in all fractures. The mean ± SD time of final follow-up radiographs and ESF removal was 71 ± 48 days (range 22-287 days). The case that had the fixator in place for 287 days initially did not return for follow up at the 8-week recheck as previously recommended. On presentation at 287 days after surgery, the fixator was intact with no evidence of drainage or inflammation at the fixator site. Thirty-four (62%) cases had full clinical outcome and 21 of 55 (38%) were determined to have an acceptable outcome at the time of ESF removal. No case was described as having an unacceptable outcome.

4 | DISCUSSION

We evaluated the use of linear ESF in minimally invasive fashion for the treatment of nonarticular tibial fractures. In this retrospective study of 49 dogs and 6 cats, linear ESF applied using minimally invasive techniques appears to be an effective and versatile method of treatment for nonarticular tibial fractures with or without the use of intraoperative imaging.

All cases were treated with minimally invasive principles. The mean ± SD mMPTA and mMDTA were similar to previously reported normal values in dogs and cats.[22,28] The mean ± SD TPA of both dogs and cats were less than previously reported normal values.[23,28,29] Recurvatum may be explained by under-reduction during surgery due to a hanging limb technique. Use of the hanging limb technique can lead to cranial malalignment of the distal bone segment, especially in very distal fractures, due to the angle of tarsus and the pull of the common calcaneal tendon. A lower than normal TPA was also considered acceptable during surgery if rotation and frontal alignment were appropriate. Due to the retrospective nature, normal contralateral limb alignment was unable to be measured. No negative consequences in outcome were noted at final follow up.

The use of intraoperative imaging led to decreased surgery time and was beneficial for real-time assessment of reduction, alignment, and implant position but did not lead to improved alignment. Cabassu[30] also reported acceptable postoperative alignment with minimally invasive plate osteosynthesis using fracture reduction under the plate without intraoperative imaging; however, 12% of cases required immediate revision surgery. In the current study, no cases required immediate revision surgery. External skeletal fixation allows small adjustments to be performed in the postoperative period and is an advantage over internal fixation especially if intraoperative imaging is not available. Due to the retrospective nature of this study, adjustments in the immediate postoperative period were not always recorded.

Most fractures were treated using a hanging limb technique (49/55).[25] Using this technique, the surgeon can align the tibia in all planes using the weight of the animal to help with distraction of the fracture. Additional adjustment to alignment was performed after placing the most proximal and distal pins using the ESF as a reduction apparatus. External skeletal fixator-like devices have recently been used for this purpose when performing minimally invasive plate osteosynthesis successfully.[31–33] Given the absence of improvement in alignment using intraoperative imaging, the benefits of using intraoperative imaging should be weighed carefully against potential safety concerns.

The overall ESF associated complication rate in this study was high at 40% with the large majority (82%) of these complications considered minor. The complication rate seen in the current study is similar to the previously reported complication rates of ESF used in the tibia.[19] The most common minor complication was pin-tract morbidity. Pin-tract morbidity remains one of the most important complications of ESF, compromising otherwise successful treatment.[1] It was reported in 18 of 55 (33%) cases. Cultures of the pin tract were not performed in any of the cases that developed pin-tract erythema, swelling, and/or discharge. Previously reported rates of pin-tract morbidity vary widely due to differences in the definition of infection and the retrospective nature of many of these studies.[19,34] Pin-tract morbidity should be considered an expected sequela of ESF due to soft-tissue irritation from implants.

The majority of pin-tract complications were associated with the lateral aspect of the proximal full pin in type II constructs. Radiographic evidence of pin loosening was evenly distributed between proximal and distal pins, indicating that external evidence of pin-tract morbidity may not be associated with pin loosening. The pin-loosening rate may have been affected by the number of pins used in the ESF, as 46% of ESF constructs only had 4 total pins placed. External pin-tract morbidity may be reduced by the addition of fixation pins and avoiding proximal lateral pin placement when possible.[16] Despite the high frequency of pin-tract morbidity and infections, ESF implants are easily removable, and minor short-term morbidity associated with superficial pin-tract infection often resolves following topical antibiotic treatment, and adequate pin care or removal.[6,19,35,36]

Deep pin-tract infection leading to osteomyelitis was noted in a single case, which had sustained a type 1 open fracture of the tibia when hit by a car. Although only reported in a single case, the tibia may be more at risk of deep pin-tract infections secondary to the limited soft-tissue coverage over the medial aspect of the tibia leading to poor extraosseous blood supply and reduced intramedullary blood supply in the early stages following fracture, especially with highly traumatic fractures.[19] As the causative agent of pin tract infection is often a skin contaminant, the limited soft-tissue envelope over the tibia would increase the risk for penetrating infection.[19,37] This is further supported by the finding that open fractures were associated with major complications.

This study had many limitations inherent to the retrospective design. Cases were collected over a long period of time with multiple different surgeons contributing, which created variation in technique and case management. This may have led to differences in the reporting of complications and could have introduced bias into the selection of cases for intraoperative imaging. Given the variability in reporting, direct comparison with findings reported in other studies is not possible, especially with regard to time to union. Contralateral tibial radiographs were not available to evaluate alignment between limbs and the effect of tibial shortening. Due to the retrospective nature of the study, long-term follow up was not available after fixator removal, which may have led to unreported complications in the postconvalescent period. Finally, a second treatment group of tibial fractures treated with other fixation methods to compare outcome was not included.

In conclusion, ESF placed using minimally invasive techniques, with or without intraoperative imaging, allowed near anatomic frontal and rotational alignment and is an effective treatment for nonarticular tibia fractures. Most of the complications were minor, self-limiting, and did not affect short-term outcome. Future prospective studies including contralateral limb radiographs and long-term follow up are warranted to further investigate alignment, long-term complications, and outcomes.

ACKNOWLEDGMENTS

Author Contributions: Sherman AH, DVM: Contributed to the design of the study; acquisition, analysis, and interpretation of the data, and drafting of the manuscript. Kraus KH, DVM, MS, DACVS: Contributed to the design of the study; acquisition, analysis, and interpretation of the data, and drafting of the manuscript. Watt D, DVM: Contributed to the design of the study and acquisition of data. Yuan L, BS: Contributed to statistical design, analysis, and interpretation of the data. Mochel JP, DVM, MS, PhD, DECVPT, AAVPT Fellow: Contributed to statistical design, analysis, and interpretation of the data. All authors gave their final approval of the manuscript. Open access funding provided by the Iowa State University Library.

CONFLICT OF INTEREST

The authors declare no conflicts of interest related to this report.

REFERENCES

1. Hayashi K, Kapatkin AS. Fractures of the tibia and fibula. In: Johnston SA, Tobias KM, eds. *Veterinary Surgery: Small Animal*. 2nd ed. Elsevier Saunders; 2018:1176-1193.
2. Boone EG, Johnson AL, Montavon P, Hohn RB. Fractures of the tibial diaphysis in dogs and cats. *J Am Vet Med Assoc*. 1986; 188:41-45.

3. Dudley M, Johnson AL, Olmstead M, Smith CW, Schaeffer DJ, Abbuehl U. Open reduction and bone plate stabilization, compared with closed reduction and external fixation, for treatment of comminuted tibial fractures: 47 cases (1980–1995) in dogs. *J Am Vet Med Assoc*. 1997;211:1008-1012.
4. Guiot LP, Déjardin LM. Prospective evaluation of minimally invasive plate osteosynthesis in 36 nonarticular tibial fractures in dogs and cats. *Vet Surg*. 2011;40(2):171-182.
5. Johnson AL, Kneller SK, Weigel RM. Radial and tibial fracture repair with external skeletal fixation: effects of fracture type, reduction, and complications on healing. *Vet Surg*. 1989;18:367-372.
6. Piermattei DL, Flo GL, DeCamp CE. Fractures of the tibia and fibula. *Brinker, Piermattei and Flo's Handbook of Small Animal Orthopedics and Fracture Repair*. 5th ed. Saunders; 2016:633-660.
7. Reems MR, Beale BS, Hulse DA. Use of a plate–rod construct and principles of biological osteosynthesis for repair of diaphyseal fractures in dogs and cats: 47 cases (1994–2001*). J Am Vet Med Assoc*. 2003;223:330-335.
8. Perren SM. Evolution of the internal fixation of long bone fractures. The scientific basis of biological internal fixation: choosing a new balance between stability and biology. *J Bone Joint Surg Br*. 2002;84:1093-1110.
9. Baroncelli AB, Peirone B, Winter MD, et al. Retrospective comparison between minimally invasive plate osteosynthesis and open plating for tibial fractures in dogs. *Vet Comp Orthop Traumatol*. 2012;25:410-417.
10. Déjardin LM, Cabassu JB, Guillou RP, Villwock M, Guiot LP, Haut RC. In vivo biomechanical evaluation of a novel angle-stable interlocking nail design in a canine tibial fracture model. *Vet Surg*. 2014;43(3):271-281.
11. Schmokel HG, Hurter K, Schawalder P. Percutaneous plating of tibial fractures in two dogs. *Vet Comp Orthop Traumatol*. 2003;16:191-195.
12. Schmokel HG, Stein S, Radke H, et al. Treatment of tibial fractures with plates using minimally invasive percutaneous osteosynthesis in dogs and cats. *J Small Anim Pract*. 2007;48:157-160.
13. Aronsohn MG, Burk RL. Unilateral uniplanar external skeletal fixation for isolated diaphyseal tibial fractures in skeletally immature dogs. *Vet Surg*. 2009;38(5):654-658.
14. Johnson AL, Seitz SE, Smith CW, Johnson JM, Schaeffer DJ. Closed reduction and type-II external fixation of comminuted fractures of the radius and tibia in dogs: 23 cases (1990–1994). *J Am Vet Med Assoc*. 1996;209(8):1445-1448.
15. Johnson AL, Schaeffer DJ. Evolution of the treatment of canine radial and tibial fractures with external fixators. *Vet Comp Orthop Traumatol*. 2008;21(3):256-261.
16. Kraus KH, Wotton HM, Boudrieau RJ, Schwarz L, Diamond D, Minihan A. Type-II external fixation, using new clamps and positive-profile threaded pins, for treatment of fractures of the radius and tibia in dogs. *J Am Vet Med Assoc*. 1998;212(8):1267-1270.
17. Ness MG. Treatment of inherently unstable open or infected fractures by open wound management and external skeletal fixation. *J Small Anim Pract*. 2006;47(2):83-88.
18. Beale B, McCally R. Minimally invasive fracture repair of the tibia and fibula. *Vet Clin*. 2020;50(1):183-206.
19. Beever LJ, Giles K, Meeson RL. Postoperative complications associated with external skeletal fixators in dogs. *Vet Comp Orthop Traumatol*. 2018;31(2):137-143.
20. Palmer RH. External fixators and minimally invasive osteosynthesis in small animal. *Vet Clin*. 2012;42(5):913-934.
21. Zheng K, Li X, Fu J, et al. Effects of Ti2448 half-pin with low elastic modulus on pin loosening in unilateral external fixation. *J Mater Sci Mater Med*. 2011;22(6):1579-1588.
22. Dismukes DI, Tomlinson JL, Fox DB, et al. Radiographic measurement of the proximal and distal mechanical joint angles in the canine tibia. *Vet Surg*. 2007;36:699-704.
23. Dismukes DI, Tomlinson JL, Fox DB, et al. Radiographic measurement of canine tibial angles in the sagittal plane. *Vet Surg*. 2008;37(3):300-305.
24. Cook JL, Evans R, Conzemius MG, et al. Proposed definitions and criteria for reporting time frame, outcome, and complications for clinical orthopedic studies in veterinary medicine. *Vet Surg*. 2010;39(8):905-908.
25. Kraus KH, Toombs JP, Ness MG. Tibia. In: Kraus KH, Toombs JP, Ness MG, eds. *External Fixation in Small Animal Practice*. 1st ed. Blackwell Science Ltd; 2003:145-181.
26. DeCamp CE, Johnston SA, Dejardin LM. Fractures: classification, diagnosis and treatment. *Brinker, Piermattei and Flo's Handbook of Small Animal Orthopedics and Fracture Repair*. 5th ed. Saunders; 2016:24-152.
27. Roe SC. External fixators, pins, nails and wires. In: Johnson AL, Houlton JE, Vannini R, eds. *AO Principles of Fracture Management in the Dog and Cat*. AO Publishing; 2005:52-57.
28. Palumbo AP, Salvaggio A, Volta A, et al. Good inter- and intraobserver reliability for assessment of radiographic femoral and tibial frontal and sagittal planes joints angles in normal cats. *Vet Comp Orthop Traumatol*. 2020;33(5):308-315.
29. Schnabl E, Reese S, Lorinson K, Lorinson D. Measurement of the tibial plateau angle in cats with and without cranial cruciate ligament rupture. *Vet Comp Orthop Traumatol*. 2009;22(2):83-86.
30. Cabassu J. Minimally invasive plate osteosynthesis using fracture reduction under the plate without intraoperative fluoroscopy to stabilize diaphyseal fractures of the tibia and femur in dogs and cats. *Vet Comp Orthop Traumatol*. 2019;32(6):475-482.
31. Gilbert ED, Lewis DD, Townsend S, Kim SE. Comparison of two external fixator systems for fracture reduction during minimally invasive plate osteosynthesis in simulated antebrachial fractures. *Vet Surg*. 2017;46(7):971-980.
32. Townsend S, Lewis DD. Use of the minimally invasive reduction instrumentation system for dacilitating alignment and reduction when performing minimally invasive plate osteosynthesis in three dogs. *Case Rep Vet Med*. 2018;2018:2976795.
33. Von Pfeil DJF, Horstman C. Development of a novel fracture fragment stabilization system for minimally invasive osteosynthesis and in vitro comparison to traditional Kern bone reduction forceps. *Vet Surg*. 2020;49(7):1350-1358.
34. Rovesti GL, Bosio A, Marcellin-Little DJ. Management of 49 ante-brachial and crural fractures in dogs using circular external fixators. *J Small Anim Pract*. 2007;48(4):194-200.
35. Fitzpatrick N, Riordan JO, Smith TJ, Modlinska JH, Tucker R, Yeadon R. Combined intramedullary and external skeletal

fixation of metatarsal and metacarpal fractures in 12 dogs and 19 cats. *Vet Surg*. 2011;40(8):1015-1022.
36. Kirkby KA, Lewis DD, Lafuente MP, et al. Management of humeral and femoral fractures in dogs and cats with linear-circular hybrid external skeletal fixators. *J Am Anim Hosp Assoc*. 2008;44(4):180-197.
37. Respet PJ, Kleinman PG, Meinhard BP. Pin tract infections: a canine model. *J Orthop Res*. 1987;5(4):600-603.

How to cite this article: Sherman AH, Kraus KH, Watt D, Yuan L, Mochel JP. Linear external skeletal fixation applied in minimally invasive fashion for stabilization of nonarticular tibial fractures in dogs and cats. *Veterinary Surgery*. 2022;1-8. doi:10.1111/vsu.13911