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CLINICAL EFFICACY AND SAFETY OF EXTERNAL FIXATORS USED IN ANTEBRACHIAL AND CRURAL FRACTURES IN DOGS: A REVIEW AND META-ANALYSIS

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Abstract

PURPOSE: The aim of this meta-analysis is to describe the indications, preoperative assessment, surgical technique, postoperative care, clinical results and complications of external fixators used to treat antebrachial and crural fractures in dogs.
METHODS: Databases including Pubmed, Elsevier, Science Direct, Cochrane library and other journals were searched for articles published before January 2018 for studies regarding history, clinical applications, complications, advantages and disadvantages of the external fixators technique.
With a history of over a hundred years, external skeletal fixators have been used in veterinary medicine as a common technique for stabilizing fractures over the past two decades. The external skeletal fixators use multiple percutaneous pins or wires placed distally and proximally to the fracture site or joint, coupled with an external frame, that can be linear, circular or hybrid and can be placed in various geometrical configurations. This method can be used in various situations besides fracture stabilization, including joint immobilization, limb lengthening and angular, translational and rotational limb deformities, external skeletal fixators being mechanically versatile. The minimal soft tissue and bone trauma allows for simple staged disassembly in helping promotion of bone healing by using increased loading forces on the fracture site after the beginning of healing. Also, from the reviewed sources we can easily say that some of the most common postoperative complications of these surgical approaches are pin-tract infections, bone lysis, osteomyelitis and implant failure but none of them outweigh the benefits.
CONCLUSIONS: External skeletal fixators are a biologically friendly surgical technique, used to minimize disruption of the blood supply to the soft tissue and bone being an advantageous system for management of antebrachial and crural fractures in dogs.

Key words: *dog, external fixators, orthopaedics, review, veterinary surgery.*

INTRODUCTION AND HISTORY

Every fracture has its own characteristics that make it suitable usually for a single, best, repair method. However, more than often, a number of equally valid management methods can be used and, of these, external skeletal fixation is one of the more versatile treatment options available to the surgeon (Kraus et al., 2003).
Surgery has always been dominated by the fear of pain and lethal infections. As early as the year 400 BC, Hippocrates held the opinion that immobilisation should be the aim following realignment and only if necessary and in very few cases did he use open surgery techniques for fracture repair (Adams, 1939).
After Hippocrates, in the first part of the nineteenth century, Joseph-François Malgaigne (1806-1865), a French surgeon and a medical historian, is considered to be the first to devise and to apply a practical method of external skeletal fixation, his method being used in the treatment of displaced transverse fractures of the patella, and consisted of two double hooks, which were inserted through the skin and engaged into the upper and lower borders of the patella. The hooks were connected by a screw, which drew the fragments into apposition and maintained them in position during the healing period (Malgaigne, 1847).
An adapted form of Malgaigne's screw technique was developed by Von Heine (1878), a professor of Surgery in Prague. His method involved drilling a hole through the cortical layers of the bone fragments near the fractured ends, perpendicular to the longitudinal axis,

and pushing through the holes ivory pins and fixing them in plaster of Paris by means of a Some historians consider Clayton Parkhill (1860-1902), professor of Surgery at the Gross Medical School in Denver, to be the one that first described external skeletal fixators in 1897, who designed and used a special external clamp to aid transfixation pins to be placed into long bones and to externally stabilize the fracture. (Martinez, DeCamp, 2012 -Tobias). His device consisted of four screws, two of which were inserted into each fracture fragment and the external ends of the screws were fixed together by means of a series of small plates and bolts (Parkhill, 1897; Parkhill, 1898).

In Europe, the father of external fixation devices is considered to be Albin Lambotte (1866-1955), who designs a similar apparatus as Parkhill for fractures of the femur, tibia, forearm, humerus, clavicle and metacarpals. His apparatus had the advantage over Parkhill's that it needed no additional fixation other than that provided by the 'fixateur'. His method used sharp ended pins fixed only in the cortex, inserted parallel to each other, two pins proximal and two pins distal to the fracture site, at 2 cm away, and sometimes cerclage in the case of oblique fractures (Hernigou, 2016).

The early forms of external skeletal fixation in veterinary medicine included the Stader reduction and fixation splint (1937), the Angell Memorial Animal Hospital splint (1938) and the Kirschner-Ehmer fixation splint (1940) (Petit, 1992). Despite positive reports, the use of external skeletal fixators remained limited due to relatively high complication rates, such as premature pin loosening, pin tract sepsis and associated delayed union or nonunion fractures. The development of proper transfixation pin insertion techniques and advances in pin design resulted in enhanced longevity of the pin-bone interface, which led to fewer complications. Advances in biomechanics of external skeletal fixator frame configurations led to a better knowledge of how different geometric configurations could provide mechanical support in veterinary patients with long bone fractures. Furthermore, discoveries of advanced mechanical properties using hybrid frames (e.g. type Ia/IIb or linear/circular) and tie-ins (additional connecting bars to transfixation pins or directly to intramedullary pins) have enhanced the use tube and clamps. This is considered the first form of external fixation (Hernigou, 2016). of external skeletal fixators in complex fractures (Martinez et. DeCamp, 2012, Tobias). They are now being used extensively for the treatment of long bone fractures and nonunions distal to the elbow and stifle joints, for the treatment of limb deformities and for other applications, being the standard of care in both human and veterinary orthopaedics for almost 30 years (Marcellin-Little, 2003).

COMPONETS AND TYPES OF EXTERNAL SKELETAL FIXATORS

The external skeletal fixator (ESF) system uses stainless steel pins or Kirschner wires placed percutaneously and attached to external clamps. The exposed portions of the fixation pins or wires are interconnected using connecting clamps that fasten the fixation pins to one or multiple connecting bars. Single connecting clamps are used to fasten pins to connecting bars, whereas double connecting clamps are used for connecting bars to one another (Andrerson et al., 1993).

For years, the Kirschner-Ehmer (KE) apparatus was the most commonly used system of external skeletal fixation in veterinary orthopaedics (Sherman et al., 2004). Recently, there have been developed new and improved systems, that have better biomechanics (stiffness) and allow for much simpler constructs.

The external frame of the system was at first constructed of metal or acrylic (polymethylmetacrylate) connecting bars (Willer et al., 1991), but the development of titanium and especially aluminium and carbon fibre rods have dramatically imaproved the stiffness of ESF constructs, so much that many of the cases that required 2 or more stainless steel bars now achieve superior rigidity with a single bar (Bronson et al., 2003).

Linear External Skeletal Fixation Systems

Linear ESF systems are created by using transfixation pins or Kirschner wires that can be connected to a simple bar (type Ia frame, unilateral), two connecting bars opposed 90 degrees (type Ib frame, unilateral biplanar); two connecting bars opposed 180 degrees (type IIa or IIb frame, bilateral); or three connecting bars, two connecting bars opposed 180 degrees with one connecting bar opposed 90 degrees from the other two (type III frame, bilateral biplanar) (Fig. 1) (Johnson et al., 1999).

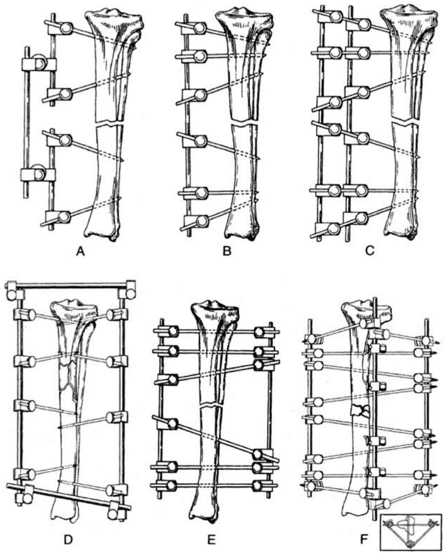

Figure 1. Common linear external skeletal fixator systems. A. type Ia, double clamp; B. type Ia, single connecting bar; C. type Ia, double connecting bar; D. type Ib; E. type II; F. type III (Adapted from Piermattei, D.L., Flo, G.L., Handbook of Small Animal Ortopedics and Fracture repair, ed. 3, Philadelphia, WB Saunders, 1997, pp. 82-85)

The most commonly used linear ESF system is the Kirschner-Ehmer (KE) splint, that comes in three sizes: small, for cats and small dogs; medium, for medium and large dogs; and large, for giant breed dogs and other species (Bouvy et al., 1993).

Another type of linear ESF is the one using acrylic pin splints, that have an acrylic column that acts as both the connecting rod and transfixation pin-gripping device. The major advantage of acrylic pin splints is that the connecting bar can be contoured to match any fracture configuration, body or joint angle and the fact that pins can be placed at any location without the difficulty of passing them through clamps, being best suited for mandibular and transarticular applications (Egger, 1992).

Circular External Skeletal Fixation Systems

Circular fixators (CEF) or ring fixators use supporting rings, connection rods, bolts and tensioned transfixation Kirschner wires (Fig. 2). The method used for placement of circular external skeletal fixation is termed the *Ilizarov method* (Marcellin-Little, 1999).

Figure 2. Full-ring circular external skeletal fixation system applied for tibia lengthening (Adapted from Zamani, A.R., Oyadij, S.O., Analytical modelling of Kirschner wired in Ilizarov circular external fixators as pretensioned slender beams, Journal of the Royal Society Interface 2009, 6:243-256)

Circular ESF systems share many of the attributes that make linear external skeletal fixation systems well suited for management of antebrachial and crural fractures in dogs. Both types of systems can be applied using closed or open fracture reduction, being useful for stabilizing highly comminuted fractures that can not be anatomically reconstructed, but circular systems have a higher bending stiffness combined with a lower axial stiffness, establishing better conditions for bone healing (Fleming et al., 1989).

Circular fixators use smaller diameter wires as fixation elements (Lewis, 2001). The fixation wires are tensioned so that construct stiffness increases, but weight bearing produces axial micromotion of the stabilized segments, which is thought to aid fracture healing (Egger et al., 1993). Given the fact that the fixation wires and pins are placed in multiple planes, soft-tissue trauma is reduced and early weight bearing in the convalescenteriod is encouraged (Ilizarov, 1992).

Fixators are constructed using three to five, but generally four rings, with two rings used to secure each of the major fracture segments. The most proximal and distal rings are usually positioned near their respective metaphyses of the fractured bone and the intermediate rings can be placed over the intact bone, adjacent to the fracture (Marcellin-Little, 1999a).
Constructs can be single-block, when the threaded bars connecting the rings cover the entire length of the limb and double-block constructs, when two separate ring blocks stabilize each fracture segment (Andreson et al., 2003).
Circular fixators can also be used for stabilizing a variety of long bone fractures, spinal fractures and luxations (Wheeler et al., 2007), to dynamically correct angular limb deformities (Lewis et al., 1999a) and to provide a rigid fixation for arthrodesis (Lewis et al., 1999b).
This type of fixation requires a high level of post-operative care and some drawbacks of this method can be the possibility of suboptimal fracture reduction, loss of limb function if transfixation wires impede muscle motion and the potentially high risk for sepsis along the wire tracts (Anderson et al., 2003).

Hybrid External Fixation Systems
Hybrid external fixation systems (HEF) are a new emerging technique for fracture stabilization in veterinary orthopaedic surgery. They combine elements from both linear and circular fixators that can be connected in a high number of combinations (Jimenez-Heras et al., 2014).
Hybrid systems have been applied for correction of growth deformities and fracture repair (Farese et al., 2002; Sereda et al., 2009).
Due to combination of both linear and circular elements, HEFs require a reduced number of rings comparatively to circular systems that usually require three or four rings, being less cumbersome and better tolerated by the patient (Kirkby et al., 2008) (Fig. 3). Hybrid fixators also share some of the positive characteristics of circular fixators like small-diameter wires that allow the fixation of small bone fragments and enable axial micro-motion, stimulating callus formation and accelerating bone healing (Goodship and Kenwright, 1985).

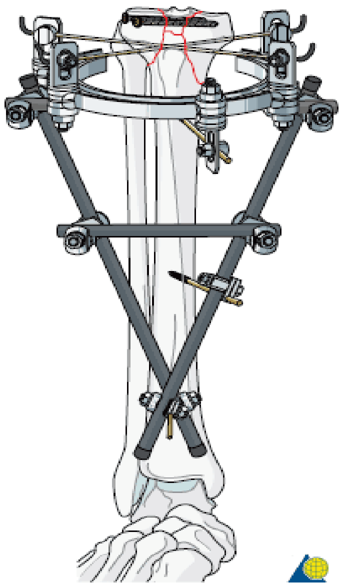
Figure 3. Hybrid fixator used for a tibial plateau fracture (Adapted from Ruedi, T.P., Buckley, R., Moran, C.G., AO Principles of Fracture Management, Ann R Coll Surg Engl, 2009, 91(5):448-449)

This type of fixation is very useful in fractures with short juxta-articular fragments, in which the circular component is used for stabilization of the small fragment while the linear component is used for the long one, but can also be useful in transverse, oblique or diaphyseal fractures (Clarke and Carmichael, 2006).
Published reports describe the use of hybrid fixation systems for fracture repair in dogs and cats and a classification of these fixators is already being reviewed (Hudson et al., 2014).
Hybrid systems can also be classified based on their ring number (Jimenez-Heras, 2014):
I. one ring included in the frame;
II. two rings included in the frame;
III. three or more rings included in the frame;
or by the number of linear elements:
A: One linear element included in the frame;
B: Two linear elements included in the frame;
C: Three linear elements included in the frame;
D: Four or more linear elements included in the frame.
Some studies have started using **Minimally Invasive Reduction Instrumentation Systems (MIRIS)** in veterinary orthopaedics, a type of minimally invasive external fixator system

developed to facilitate applications of minimally invasive plate osteosynthesis (MIPO) in human pacients (Gilbert et al., 2016).

GUIDING PRINCIPLES OF EXTERNAL SKELETAL FIXATOR APPLICATION

External skeletal fixators have been utilised for almost every bone, but for dogs and cats they are thought to be best suited in the distal limb, specifically the antebrachial region (radius/ulna) and crural region (tibia) (Harari et al., 1996, Johnston et al., 2008).

Selection of the appropriate external skeletal fixation system is always based on factors including fracture biomechanics, aetiology, location and configuration and also patient health status, age, body weight, lameness score and concurrent musculoskeletal injuries.

Due to the fact that fracture healing is completely dependent on maintaining the blood supply to the fracture site during all phases of bone healing all fixation systems used must protect, preserve and enhance vascularization at the fracture site, a method of fracture management known as *biological fixation* (Palmer, 1999).

External skeletal fixation systems meet the criteria, being a fracture stabilization method that can be applied both through a closed and open approach of the fracture site, with the surgical goal of a required open approach kept to a minimum (Martinez and DeCamp, 2012).

From the papers studied fifteen critical principles have been established for the application of external skeletal fixators for fracture management (Piermattei et al., 2006a, Brinker and Flo, 1975):

1. Aseptic techniques should be used in order to obtain a successful bone healing.
2. A proper bone surface location should be used for insertion of transfixation pins, in order to maximize construct stabilization and minimize soft-tissue damage (the proper surface for tibia fractures is medial and for radius fractures medial or craniomedial) (Marti and Miller, 1994a, 1994b).
3. The most suitable configuration of the external fixator system should be selected in order to obtain the best stabilization of the intended bone(s). Limitations of frame configurations for various regions should be taken into consideration, as well as the need for counteracting specific biomechanical forces. Frame selection will ultimately be dictated by careful consideration of both factors associated with the patient and with fracture management (Egger et al., 1986; Brinker et al., 1985; Egger, 1983).
4. Auxiliary fixation should be used when indicated. In order to achieve maximal stabilization of fracture fragments, auxiliary fixation such as intramedullary pins, lag screws, Kirschner wires and cerclage may be helpful during insertion of the external skeletal fixation pins (Aron et al., 1991, Popkov et al., 2014).
5. Fracture stabilization and reduction should be maintained during application of the external fixator frame, in order to minimize soft-tissue trauma and discomfort of the animal (Piermattei et al., 2006).
6. Insertion of pins and/or Kirschner wires through soft tissues should be made in a manner that does not distort or capture the surrounding tissues.
7. Proper pin drilling or Kirschner wire insertion technique is critical in order to maintain system integrity during bone healing and can be obtained by using a high-power drill at low speed (<150 rpm) in order to prevent thermal damage to the bone, which can result in bone resorption or pin loosening (Egger et al., 1986).
8. Proper insertion of pins or Kirschner wires through both cortices of the bone, in order to avoid weakness at the pin-bone interface or pin loosening (Dernell et al., 1993).
9. Insertion of smooth and negative-threaded-profile pins at an angle of 70 degrees to the long axis of the bone in order to obtain maximum stiffness of the fixator along with maximum pull-out resistance from the bone (Egger, 1993; Bouvy et al., 1993).
10. Insertion of pins or Kirschner wires used to create an external linear or circular skeletal fixator system in the same plane, in order to reduce pin-bone interface stress and premature resorption of bone due to unnecessary bending forces or stiff double clamps.
11. Insertion of pins or Kirschner wires at target points on the bone fragment in order to optimize the mechanical stability of the external fixation system. Studies show that maximum stability can be obtained by inserting

pins near the proximal and distal ends of the bone fragment rather than by inserting all the pins near the ends or near the fracture site (Toombs, 1994).

12. Insertion of two to four transfixation pins or Kirschner wires in each major bone fragment, in order to obtain greater stability. Studies since the 1970s have shown that three to four pins per fracture fragment increase the stiffness of the construct (Hamish et al., 2000). Using more than four pins does not increase the mechanical strength of the external skeletal fixation system (Egger, 1993; Brinker et al., 1985; Palmer et al., 1992).

13. Selection of transfixation implants, connecting bars, rings and transfixation pins of optimal size for the size of the bone involved.

14. Placement of connecting bars at an optimal distance between the pin-connecting bar clamps and the patient's skin, taking into consideration the size of the patient and the anticipated post-surgical swelling. After 10 days of usual post-surgical swelling the system might need readjustment (Piermattei et al., 2006).

15. Use of cancellous bone graft in cases of significant cortical defects, especially for architectural deficits in mature and older animals, in those with osteotomies of diaphyseal bone and in cases of nonunions (Johnson et al., 1989).

Post-operative care of ESF systems

Post-operative management of external fixators is quite controversial, the veterinary literature offering recommendations for bandaging the frames, leaving the frames uncovered, bandaging frames only in the early postoperative period and daily hydrotherapy (Harari, 1992).

In most cases gauze sponge dressings may be placed between the skin and bar-connecting clamps in order to absorb any discharge or blood from the pin-skin interface for about 5 to 7 days post-operatively. Dressings need to be changed daily until discharge stops. The frame should be bandaged in order to prevent it from getting in contact with other objects and in order to protect the patient (Lethaby et al., 2013).

If open wounds exist, they need to be treated appropriately on a daily basis. Some studies suggest allowing a dry, protective crust to form at the pin-tract drainage site, while others recommend daily cleaning with antiseptic solutions (Phillips et al., 1991).

Animals should be rechecked every few weeks and the clamps should be adjusted and tightened. Radiographs should be taken monthly in order to evaluate bone healing and decide on the best time to start disassembly of the frame. Destabilization of a type III frame to a type I 6 weeks post-operatively has been shown to enhance fracture remodelling (Egger and Histand, 1993).

Most uncomplicated fractures in adult dogs treated with ESF heal in 2 to 3 months by means of periosteal and endosteal callus formation (Harari et al., 1998).

Fixation of distal extremity fractures: radius and tibia

Radial and tibial fractures account for 30 per cent of all fractures in small animals (Ness et al., 1996) and external skeletal fixation (ESF) is a common method of stabilisation (Egger et al., 1985; Roe et al., 1985; Johnson et al., 1989; Pettit, 1992; Piermattei and Flo, 1997).

Most fractures of the radius and tibia may be treated in a closed manner and depending on the type of fracture (open or closed, comminuted or simple) with either linear, circular or hybrid external fixator frames.

External skeletal fixation systems are particularly useful in fractures of the radius and ulna due to the relative lack of surrounding soft-tissue, being the standard of care in open fractures, delayed unions, nonunions and corrective osteotomies (McCartney et al., 2010). Insertion of pins should be made on the medial or craniomedial side of the radius, the bone being more superficial on this location and the external fixator being in the position of least interference from other objects. All the linear configurations (types Ia, Ib, IIa and IIb frames) can be used, along with circular and hybrid linear-circular fixators. Type Ia frames are best suited for stabilizing simple fractures of the radius and ulna in toy breed dogs and cats, while type Ib can be usually used for comminuted fractures (Marti and Miller, 1994a, b). Circular external fixators or hybrid fixator provide an excellent alternative when a linear frame cannot be used due do severe soft-tissue trauma or in case of short fracture segments (Piermattei and Flo, 2006).

All external skeletal fixation systems can be used for tibial fractures (open or closed, simple or comminuted), more complex frames being used accordingly to the complexity of the fracture, tissue trauma and patient weight. All types of frames are applicable to the tibia, because the medial, cranial and lateral surfaces of the bone are available (Bilgili et al., 2007).

Type Ia frames are best suited for fractures of skeletally immature patients, who have a tendency of healing faster than adults. Type Ib frames are usually used for stabilizing proximal and distal tibia fractures when there is limited bone stock for pin fixation in one plane, the fixation planes being oriented at approximately 90 degrees to each other. Types IIa and IIb are indicated when no load sharing is possible in complex, nonreducible fractures. Circular and hybrid frames are usually used for treatment of epiphyseal fractures, where limited bone segments are available for fixation (Witte et al., 2014).

Studies have shown that durations of bone consolidation and external fixators were shorter for radial than tibial fractures and the hypothesis that the radius heals faster than the tibia exists (Tuhoy et al., 2014).

COMPLICATIONS OF EXTERNAL SKELETAL FIXATION SYSTEMS

While external skeletal fixation may be considered the standard of care in orthopedic surgery for management of antebrachial and crural fractures, being a versatile and useful tool, complications associated with these systems need to be taken into consideration when deciding on this surgical technique (Beever et al, 2017).

Complications associated with external skeletal fixation systems may be related to the fixation device or may be due to the character of the fracture under treatment. Complications associated with the fixation device are usually common, due to the large number of components, but have few consequences for the patient or for fracture healing (Egger, 1991).

Some of the most common minor post-operative problems are pin tract infection and premature pin or transfixation wire loosening, that can be reduced by using adequately strong and stiff frames (Egger, 1992; Jonhston et al, 1989).

Slight, serous drainage and minimal tissue inflammation around the pin-skin interface is commonly observed in all types of ESF frames and appears commonly when large muscles are transfixed (Harari, 1992). Excesive movement of the pin directly contributes to infection (Yardimci et al., 2010).

Pin tract infections occur most commonly in areas of significant penetration and disruption of adjacent soft tissues, usually being easily controlled with local treatment and antibiotic therapy. In severe cases, bacterial contamination of the pin-bone or pin-skin interface takes place, leading to superficial pin tract infection, which can progress to deep pin tract infection and associated bone lysis or osteomyelitis (Krischak et al, 2002; Dudley et al., 1997).

Implant failures include pin loosening, breakage or bending; clamp loosening and connecting bar breakage, all mechanical complications that can be avoided by adhering to known guidelines concerning frame construction and pin size, type, number and location and by constructing an external skeletal fixator frame with optimal biomechanical characteristics for the fracture treated (Anderson et al., 2003). The weakest part of any ESF system is the pin-bone interface and the junction of the threaded and non-threaded parts of the pin, thus the risk of pin breakage being higher in negative profile pins (Bennet et al., 1987; Clary et al., 1995).

Complications are considered major if they require additional surgery or substantial frame modification under general anaesthesia or if they negatively influence the expected outcome (Rovesti et al., 2007).

Issues of fracture healing may be due to the primary injury, but also due to the choices in external fixator construction. ESFs are usually chosen to treat severe fractures, which may ultimately result in issues of malunion, delayed union or nonunion, attributable to the conditions of the fracture (Anderson et al., 1996; Egger et al., 1986).

Iatrogenic bone fractures are uncommon in cats, this complication usually having contributing factors such as multiple injuries, presence of empty drill holes and inappropriate post-operative exercise restriction (Knudsen et al., 2012).

Other complications that may develop with the use of ESFs are loss of range of motion at a joint due to muscle atrophy, fibrosis, contracture or all of these conditions. Joint function is maintained only by using safe corridors for pin placement and by minimizing soft-tissue trauma. Using safe corridors for pin placement also aids in avoiding vascular injury or peripheral nerve injury (Davidson, 1997; Johnson et al., 1996).

Early ambulation hastens fracture healing by promoting axial micromotion and also prevents disuse atrophy and muscle contracture in fracture patients, especially important with bilateral fractures (Lincoln, 1992; Radke et al., 2006).

CONCLUSIONS

Although there is no perfect fixation system for each type of fracture and each clinical case should be individually evaluated, external skeletal fixators can be easily customized to accommodate almost all types of fractures of the antebrachial and crural regions being the standard of care in veterinary orthopaedic surgery.

External fixators may be applied by closed or open surgical procedures and advances in technology and surgical techniques have greatly enhanced the pin-bone interface, resulting in a significant decline of complications seen with the use of any type of external fixator frame over the last recent years, making them a safe surgical technique.

Consistent successful outcomes with limited complications and patient morbidity can be easily achieved if the guiding principles for external skeletal fixation systems application are followed.

REFERENCES

Anderson, G., M., Lewis, D., D., Radasch, R., M., 2003. Circular external skeletal fixation stabilization of antebrachial and crural fractures in 25 dogs. J Am Anim Hosp Assoc., 39:479-498.

Anderson, M., A., Mann, F., A., Kinden, D., A., 1996. Evaluation of cortical bone damage and axial holding power of ninthreaded and anhanced threaded pins placed with and without drilling of a pilot hole in femurs from canine cadavres. JAMVA 208:883-887.

Aron, D., N., Foutz, T., L., Keller, W., G., 1991. Experimental and clinical experience with an IM pin external fixator tie-in configuration. Vet Comp Orthop Traumatol 4:86-94.

Beever, L., Giles, K., Meeson, R., 2017. Postoperative complications associated with external skeletal fixatiors in cats. Journal of feline medicine and surgery, 19:727-736.

Bennet, R., A., Egger, E., L., Histand, M., 1987. Comparison of the strength and holding power of 4 pin designs for use with halp pin (type I) and external skeletal fixation. Vet Surg, 16:207-211.

Bilgili, H., Kurum, B., Captug, O., 2007. Treatment of radius-ulna and tibia fractures with circular external skeletal fixator in 19 dogs. Pol J Vet Sci, 10(4):217-231.

Bouvy, B., M., Markel, M., D., et al, 1993. Ex vivo biomechanics of Kirschner-Ehmer external skeletal fixation applied to canine tibiae. Vet Surg, 22:194-207.

Brinker, W., O., Flo, G., L., 1975. Principles and application of external skeletal fixation. Vet Clin North Am Small Anim Prac, 5:197-208.

Brinker, W., O., Verstraete, M., E., Soutas-Little, R., W., 1985. Stiffness studies on various configuration and types of external skeletal fixators. J Am Anim Hosp Assoc, 21:280-288.

Bronson, D., G, Ross, J., D., Toombs, J., P., Welch, R., D., 2003. Influence of the connecting rod on the biomechanical properties of five external skeletal fixation configurations. Vet Comp Orthop Traumatol, 16:82-87.

Clarke, S., P., Carmichael, S., 2006. Treatment of distal diaphyseal fracrures using hybrid external skeletal fixation in three dogs. J Small Anim Pract, 47:98-103.

Clary, E., M., Roe, S., C., 1995. Enhancing external skeletal fixation pin performance: Consideration of the pin-bone interface. Vet Comp Orthop Traumatol, 8:1-8.

Davidson, E., B., 1997. Vascular injury and delayed hemorrhage after antebrachial external skeletal fixation in a dog. Vet Comp Orthop Traumatol 10:75.

Dernell, W., S., Harari, J., Blackletter, D., M., 1993. A comparison of acute pull-out strength between 2-way and one-way transfixation pin insertion for external skeletal fixation in canine bone. Vet Surg 22:110-114.

Dudley, M., Johnson, A., L., Olmstead, M., et al., 1997. 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, 211: 1008–1012.

Egger, E., L., 1983. Static strength evaluation of six external skeletal fixation configurations. Vet Surg, 12:130-136.

Egger, E., L., 1991. Complications of external fixation: a problem oriented approach. Vet Clin North Am Small Anim Pract 21:705.

Egger, E., L., 1993. Textbook of small animal surgery, ed. 2, Philadelphia, Saunders.

Egger, E., L., Gottsauner-Wolf, F., Palmer, J., Aro, H., T., Chao, E., Y., S., 1993. Effect of axial dynamization of bone healing. J Traum, 34:185-192.

Egger, E., L., Histand, M., B., 1986. Effect of pin insertion on bone pin interface. Vet Surg, 15:246-252.

Farese, J., P., Lewis, D., D., Cross, A., R., Collins, K., E., Anderson, G., M., Halling, K., B., 2002. Use of IMEX SK-circular external fixator hybrid constructs for fracture stabilization in dogs and cats. J Am Anim Hosp ASSoc., 38:279-289.

Gilbert, E., D., Lewis, D., D., Townsend, S., Kim, S., E., 2016. Comparison of two external skeletal fixator systems for fracture reduction during minimally invasive plate osteosynthesis in simulated antebrachial fractures. Veterinary Surgery, 2017:1-10.

Goodship, A., E., Kenwright, J., 1985. The influence of induced micromovement upon the healing of experimental tibial fractures. J Bone Joint Surg [BR], 67:650-655.

Hamish, D., R., Butterworth, S., 2000. Guide to canine and feline orthopaedic surgery. Ed. Blackwell Science LTD pages

Harari, J., 1992. Complications of external skeletal fixation. Vet Clin North Am Small Anim Prac, 22:90-107.

Harari, J., Seguin, B., Bebchuk, T., Lincoln, J., 1996. Closed repair of tibial and radial fractures with external skeleltal fixation. Comp Contin Educ Pract Vet, 18:651-664.

Harari, J., Seguin, B., Padgett, S., L., 1998. Principles of external skeletal fixation in small animal surgery. Vet Med, 445-453.

Harasen, G., 2012. Orthopedic hardware and equipment for the beginner. Part 3: External skeletal fixators. CVJ 53:201-203.

Hernigou, P., 2016. History of external fixation for treatment of fractures. International Orthopaedics (SICOT).

Hippocrates, 1939. The genuine works of Hippocrates, trans. Francis Adams. Williams and Williams, Baltimore.

Hudson, C., C., Lewis, D., D., Cross, A., R., Dunbar, N., J., Horodyski, M., Banks, S., A., Pozzi, A., 2012. A biomechanical comparison of three hybrid linear-circular external fixator constructs. Vet Surg, 41:954-965.

Ilizarov, G., A., 1992. The apparatus: components and biomechanical principles of application. Ilizarov, G.A., ed. Transosseous osteosynthesis. Theoretical and clinical aspects of the regeneration and growth of tissue. Berlin: Springer-Verlag, 63-136.

Jimenez-Heras, M., Rovesti, G., L., Nocco, G., Barilli, M., Bogoni, P., Salas-Herreros, E., Armato, M., Collivignarelli, F., Vegni, F., 2014. Evaluation of sixty-eight cases of fracture stabilisation by external hybrid fixation and a proposal for hybrid construct classification. BMC Veterinary Research, 10:189.

Johnson, A., L., Kneller, S., K., Weigal, R., M., 1989. Radial and tibial fracture repair with external skeletal fixation: effects of fracture type, reduction and complications of healing. Vet Surg, 18: 367-372.

Johnson, A., L., Schaeffer, D., J., 2008. Evolution of the treatment of canine radial and tibial fractures with external fixators. Vet Comp Orthop Traumatol, 21:256-261.

Johnson, A., L., Seitz, S., E., Smith, C., W., et al, 1996. 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 209:1445.

Kirkby, K., A., Lewis, D., D., Lafuente, M., P., Radasch, R., M., Fitzpatrick, N., Farese, J., P., Wheeler, J., L., Hernandez, J., A., 2008. Management of humeral and femoral fractures in dogs and cats with linear-circular hybrid external fixators. J An Anim Hosp Assoc., 44:180-197.

Knudsen C, Arthurs G, Hayes G, et al., 2012. Long bone fracture as a complication following external skeletal fixation: 11 cases. J Small Anim Pract, 53: 687–692.

Kraus, K., H., Toombs, J., P., Ness, M., G., 2003. External Fixation in Small Animal Practice, Blackwell Science.

Krischak, G., D., Janousek, A., Wolf, S., et al., 2002. Effects of one-plane and two-plane external fixation on sheep osteotomy healing and complica- tions. Clin Biomech, 17: 470–476.

Lethaby, A., Temple, J., Santy-Tomlinson, J., 2013. Pin site care for preventing infections associated with external bone fixators and pins (Review). The Cochrane Library, Issue 12.

Lewis, D., D., Cross, A., R., Carmichael, S., Anderson, A., M., 2001. Recent advances in external skeletal fixation. J Sm Anim Pract., 29:1135-1152.

Lewis, D., D., Farese, J., P., 2014. Circular external skeletal fixation. Bojrab MJ, ed. Current Techniques in Small Animal Surgery. 5th ed. Jackson Hole: Teton NewMedia, 828-843.

Lewis, D., D., Radasch, R., M., Beale, B., S., 1999a. Initial clinical experience with the IMEX (TM) circular external skeletal fixation system - part II: use in bone lenghtening and correction of angular and rotational deformities. Vet Comp Orthop Traumatol, 12:118.

Lewis, D., D., Radasch, R., M., Beale, B., S., 1999b. Initial clinical experience with the IMEX (TM) circular external skeletal fixation system - part I: use in fractures and arthrodeses. Vet Comp Orthop Traumatol., 12:108-117.

Lincoln, J., D., 1992. Treatment of open, delayed union and nonunion fractures with external skeletal fixation. Vet Clin North Am Small Anim Pract, 22:195-207.

Malgaigne, J., F., 1847. Traite des fractures et des luxations. J.B. Bailliere, Paris, 771-772.

Marcellin-Little, D., J., 1999a. Fracture treatment with circular external fixation. Vet Clin North Am Sm Anim Pract., 29:1153-1170.

Marcellin-Little, D., J., 1999b. Treatment of bone deformities with circular external skeletal fixation. Comp Cont Ed Pract Vet, 12:481-491.

Marti, J., M., Miller, A., 1994a. Delimitation of safe corridors for the insertion of external fixator pins in the dog 1: hindlimb. J Small Anim Pract 35:16.

Marti, J., M., Miller, A., 1994b. Delimitation of safe corridors for the insertion of external fixator pins in the dog 1: forelimb. J Small Anim Pract 35:78.

Martinez, S., A., DeCamp, C., E., 2012. External skeletal fixation, chapter 44 in Veterinary Surgery Small Animal, Karen M. Tobias & Spencer A. Johnston, ed. Elsevier, pp: 608-627.

McCartney, W., Kiss, K., Robertson, I., 2010. Treatment of distal radial/ulnar fractures in 17 toy breed dogs. Vet Rec, 166:430-432.

Ness, M., G., Abercromby, R., H., May, C., Turner, B., M., Carmichael, S., 1996. A survey of orthopaedic conditions in small animal veterinary practice in Britain. Veterinary and Comparative Orthopaedics and Traumatology 9:43-52.

Palmer, R., H., 1999. Biological osteosynthesis. Vet Clin North Am Small Anim Pract 29:1171.

Palmer, R., H., Hulse, D., A., 1992. Principles of bone healing and biomechanics of external skeletal fixation. Vet Clin North Am Small Anim Prac, 22:45-68.

Parkhill, C., 1897. A new apparatus for the fixation of bones after resection and in fractures with a tendency to displacement. Trans Am Surg Assoc., 15:251-256.

Parkhill, C., 1898. Further observations regarding the use of the bone-clamp in ununited fractures, fractures with malunion and recent fractures with a tendency to displacement. Ann Surg, 27:553-570.

Petit, G., D., 1992. History of external skeletal fixation. Vet Clin North Am. Small Animal Practice, 22:1.

Phillips, L., Blackmore, J., 1991. Kirschner-Ehmer device alone to stabilize caudal lumbar fractures in small dogs. Vet Comp Orthop Traumatol, 4:112-115.

Piermattei, D., L., Flo, G., L., DeCamp, C., E., Brinker, Piermattei, and Flo's handbook of small animal orthopedics and fracture repair, ed 4, St Louis, 2006a, Saunders Elsevier, p 77-84.

Popkov, A., V., Kononovich, N., A., Gorbach, E., N., Tverdokhlebov, S., I., Irianov, Y., M., Popkov, D., A., 2014. Bone healing by using Ilizarov external fixation combined with flexible intramedullary nailing versus Ilizarov external fixation alone in the repair of tibial shaft fractures: experimental study. The Scientific World Journal, 2014:8.

Radke, H., Aron, D., N., Applewhite, A., et al., 2006. Biomechanical analysis of unilateral external skeletal fixators combined with IM-pin and without IM-pin using finite-element method. Vet Surg, 35:15-23.

Roe, S., C., Johnson, A., L., Harari, J., 1985. Placement of multiple full pins for external fixation: technique and results in four dogs. Veterinary Surgery 14: 247-251.

Ruedi, T., P., Buckey, R., Moran, C., G., 2009. AO Principles of fracture management. Ann R Coll Surg Engl, 91(5): 448-449.

Sereda, C., W., Lewis, D., D., Radasch, R., M., Bruce, C., W., Kirkby, K., A., 2009. Descriptive report of antebrachial growth deformity correction in 17 dogs from 1999 to 2007, using hybrid linear-circular external fixators constructs. Can Vet J, 50:723-732.

Toombs, J., P., 1994. A review of the key principles of external skeletal fixation. Proceedings, ACVS Veterinary Symposium Small Animal, Washington D.C.

Tuhoy, J., L., Marcellin-Little, D., J., Griffith, E., H., 2014. Duration of bone consolidation and external fixation after distraction osteogenesis in dogs. Veterinary Surgery, 43:903-911.

Witte, P., G., Bush, M., A., Scott, H., W., 2014. Management of feline distal tibia fractures using a hybrid external skeletal fixator. J Small Anim Pract, 55(11): 571-578.

Yardimci, C., Ozak, A., Nisbet, H., O., 2010. Management of Femoral Fractures in Dogs with unilateral semicircular external skeletal fixators. Veterinary Surgery, 40:379-387.

Zamani, A., R., Oyadij, S., O., 2009. Analytical modelling of Kirschner wires in circular external fixators as pretensioned slender beams. Journal of the Royal Society Interface, 6:243-256.