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REVIEW

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A review of minimally invasive fracture stabilization in dogs and cats

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Abstract

Objective: To summarize and discuss peer-reviewed studies on minimally invasive osteosynthesis (MIO) of long bone, physeal, and articular fractures in dogs and cats.

Study Design: Invited review.

Methods: A critique of literature was performed to assess MIO feasibility, outcomes, and complications through PubMed, Scopus, and CAB abstracts research databases (2000–2020).

Results: More than 40 MIO articles have been published in the last 15 years, but most studies had small numbers, lacked control groups, and used limited outcome measures. Studies generally showed that MIO was feasible in dogs and cats with low complication rates. The current evidence does not demonstrate superior bone healing or functional outcomes with MIO when compared to standard methods. Although treatment principles, case selection, and techniques varied depending on the anatomical location, there were no salient differences in complication rates among long bones, physeal, and articular fractures treated by MIO.

Conclusion: The current available evidence and the personal experience of the authors support MIO as a promising fracture management modality. MIO can yield excellent outcomes when applied in carefully selected cases, performed by surgeons experienced in the technique. We cannot, however, conclude that MIO is superior to open fracture stabilization based on the available evidence in veterinary literature. Randomized controlled studies are warranted to prospectively compare MIO with other osteosynthesis techniques and thereby validate its role in fracture management for dogs and cats.

1 | WHAT HAVE WE LEARNED FROM PAST GENERATIONS OF SURGEONS?

Minimally invasive internal fracture stabilization dates back to the early 1940s, when the German surgeon Gerhard Künthscher introduced closed intramedullary nailing. In an attempt to improve fracture management, Künthscher established the foundations of minimally invasive fracture fixation: indirect fracture reduction and implant placement performed remote to the fracture site.[1]

During the latter half of the 20th century, however, an emphasis was placed on direct bone healing through anatomic reduction.[2,3] Initial results associated with anatomic reduction and rigid fixation were excellent, but complications, such as delayed or nonunion and infection, were problematic, particularly in comminuted fractures because open anatomic reduction potentiated fragment devascularization.[4,5] The importance of preserving osseous vascularity during plate application became evident and the concept of "open but do not touch," which had previously been established in minimally invasive nailing and external fixation,[6,7] was introduced to improve the biologic environment of plated fractures.[8] These techniques established one of the sentinel concepts of minimally invasive osteosynthesis (MIO): preservation of the soft tissue envelope. With the "do not touch" technique, a standard open approach is performed, but the region of the fracture is not disrupted during plate application.[9] This approach mitigates disturbance of the fracture hematoma, periosteum, and regional musculature, favoring early fracture healing.[10] As this technique evolved, approaches became smaller and eventually the incisions were made at the location of proximal and distal ends of the plate, remote to the fracture site.[11,12]

The development of angle stable implants was critical for the advancement of MIO. The earliest description of an angle stable implant dates back to the Zespol plate in 1991.[13] Progressive technological advancements lead to the Point Contact Fixator (PC-Fix). Tepic, who played a prominent role in designing the PC-Fix, later developed the Advanced Locking Plate System (ALPS) which is one of the many angle-stable plate designs used in veterinary orthopedics today.[14]

Other locking plate systems with innovative features were developed over time. These systems shared two critical attributes that are advantageous for minimally invasive plate osteosynthesis (MIPO) applications: (1) periosteal circulation is preserved as plate-bone contact is obviated and (2) increased stability ascribed to locking the screws into the plate, optimizing the construct for bridging applications.[15]

While these systems have improved outcomes in dogs and cats,[16–18] the past decade has been characterized by a more critical analysis of the results of MIO in human patients. Several high-level evidence-based papers investigated the outcomes and complications associated with this technique.[19–21] One of the main conclusions of these meta-analyses is that the indications for and outcomes of MIO depend on the anatomical location of the fracture. In human patients, MIPO is advocated for humeral, and calcaneal fractures,[19–21] but appears less advantageous for distal radial and femur fractures. Based on these reviews, anatomic location of the fracture plays a prominent role in deciding when to employ MIO.

While technological advancements have provided new instrumentation for MIO, successful results are still dependent on prudent decision-making and exceptional surgical technique, factors that are also critical for successful open plating. The objective of this review is to present the results of published reports of MIO in dogs and cats to assist surgeons with treatment decisions based on the best available evidence and sound scientific principles. We propose an anatomical approach to MIO, grouping the publications by long bone, articular, and physeal fractures, followed by summary sections that present clinical recommendations based on available evidence and personal experience.

2 | AN ANATOMICAL APPROACH TO MIO

The advantages of MIO vary depending on the location of the fracture. Bones with limited regional soft tissue such as the tibia and the radius may benefit from the preservation of the soft tissue envelope. The humerus and femur, which have substantial surrounding musculature, may benefit from reduced dissection which mitigates iatrogenic soft tissue trauma. In addition, performing MIPO of tibial and radial fractures is generally perceived to be technically easier than humeral and femoral fractures. Fixation principles also vary depending on fracture location. While anatomic reduction of articular and physeal fractures is critical for MIO, it is not obligatory in most MIPO applications.

Minimally invasive fracture stabilization requires a comprehensive knowledge of the regional anatomy. Anatomic landmarks traditionally used in open approaches are often concealed beneath soft tissues, and must therefore be identified by palpation and intraoperative radiography. The surgical approach itself can be challenging because the small implant application incisions limits identification of tissue layers and knowledge of the regional topographical anatomy is essential when using limited MIO approaches.[22,23]

3 | MIPO: DIAPHYSEAL LONG BONE FRACTURES

The management of diaphyseal long bone fractures using MIPO requires four steps:

- Performing indirect fracture reduction,
- Establishing plate insertion skin incisions,
- Developing an epiperiosteal tunnel, and
- Plate and screw application.

Indirect reduction techniques are used to reduce and align fracture segments during MIPO.[24,25] Indirect reduction has been referred to as "blind" manipulation of the fractured bone segments and generally employs some form of traction, toggling, or translation.[24–28]

Traction can be as simple as grasping the paw and pulling on the limb, or by wrapping the paw with tape or using an instrument, such as a towel clamp, to secure a phalanx and suspending the limb from an elevated structure or the ceiling. The latter technique is sometimes referred to as a "hanging limb prep."[24] In human patients, traction tables are used extensively to obtain alignment and reduction.[28–30] Traction tables have been developed for use in small animals.[26,27] A number of techniques have been used to facilitate alignment and reduction in small animals, including closed placement of an intramedullary pin,[31,32] percutaneous placement of reduction forceps[32,33] or interfragmentary Kirschner wires,[34,35] transient intraoperative application of external fixators,[34,36,37] use of three-dimensional (3D) printed reduction guides,[38] and application of precontoured plates.[38]

3.1 | Humeral fractures

Closed placement of an intramedullary pin is the most common indirect reduction technique advocated for MIPO of humeral fractures.[24,31,32,34,39,40] Pozzi and Lewis described lateral plate insertional incisions and lateral plate placement, which is applicable to MIPO stabilization of mid- to distal diaphyseal humeral fractures.[22,41] Alternatively, Guiot et al. used a medial approach, with the intramedullary pin being inserted distally in normograde fashion from the humeral condyle via a medial distal plate insertional incision in a prospective clinical case series.[32] A medial plate-rod construct resulted in functional fracture alignment in all 15 cases with no difference in frontal or sagittal plane alignment between the fractured and the contralateral intact humerus. All fractures had anatomical or near-anatomical rotational alignment. Minor humeral shortening was detected. The mean time to osseous union was 36 days.[32] All of the dogs and cats had a complete functional recovery, based on orthopedic examination and owners' feedback at the time of the last follow-up.[32]

Advanced virtual planning and 3D printing was used to create a patient-specific fracture reduction system to facilitate MIPO stabilization of a comminuted diaphyseal humeral fracture in a cat.[38] The 3D-printed system yielded near-anatomic realignment with only 3° of varus angulation and minimal alterations in sagittal or torsional alignment or length. After 120 days, the cat had resumed normal activities and the fracture had nearly obtained complete union.[38]

3.2 | Radius and ulnar fractures

Many diaphyseal radial fractures can be successfully stabilized using MIPO.[35–37,40,42] MIPO is most applicable for comminuted fractures, but can also be utilized in transverse, short oblique, and spiral fractures, although these fractures may require a small approach to ensure anatomic reduction. Use of a traction table or a "hanging limb" preparation has been described as indirect reduction methods facilitating MIPO stabilization of the radius.[23,24,26,27]

In a retrospective study, Witsberger et al. described placing an intramedullary pin in the ulna to align the antebrachium prior to plating the radius when performing MIPO.[40] The ulnar pin also provides supplemental stability and is particularly advantageous in cats as stabilizing both the radius and ulna is advocated in this species.[43] Median time to union in dogs was 73 days. Six of eight dogs had a mild intermittent lameness, which resolved after ulnar pin removal. Clinical outcomes based on orthopedic examination at last recheck and owner feedback were deemed successful.[40]

Transient intraoperative application of an external fixator can efficiently facilitate closed indirect reduction of antebrachial fractures.[35–37,42,44] A simple circular fixator composed of two rings articulated with two or three threaded connecting rods with nuts placed on the rods proximal and distal to both rings can be used to facilitate indirect closed reduction prior to plate placement.[36,37,42,44] The construct can be used to distract and align the fracture as well as stabilize the radius during plate placement. The fixator is removed following screw placement.[36,37,42,44]

In a retrospective study, Pozzi et al. reported acceptable fracture alignment in all radius and ulna fractures stabilized using MIPO facilitated by a transient circular construct application during surgery.[36] Although mediolateral translation was significantly greater in fractures stabilized via MIPO compared to open plate application, frontal plane angulation did not differ between groups and the degree of translation was not considered to be clinically detrimental in any dog.[36] Limb function was deemed normal in all the cases based on clinical examination at the last follow-up.

When investigating the healing of radius and ulna fractures in a prospective clinical study in a cohort of 16 dogs, fractures stabilized by MIPO facilitated by a circular fixator had more rapid radiographic (mean $\pm$ SD: 30 ± 10 days) and ultrasonographic (mean $\pm$ SD: 26 ± 11 days) bone healing with greater callus formation than fractures stabilized by open reduction and plating (mean $\pm$ SD radiographic healing: 64 ± 10 days; ultrasonographic healing: 57 ± 19 days).[37] Postoperative clinical outcomes were not reported.[37]

The Minimally Invasive Reduction Instrumentation System (DePuy Synthes Trauma, West Chester, Pennsylvania) is a unilateral, linear fixator system marketed to facilitate MIPO applications in human patients.[45] The system was associated with shorter reduction times and simplified plate placement and yielded similar reduction and alignment to MIPO stabilizations facilitated using a circular construct in a canine cadaveric study.[44] The use of the Minimally Invasive Reduction Instrumentation System has been reported in a short case series of three dogs.[35] The Minimally Invasive Reduction Instrumentation System was used to assist MIPO in one dog with a short spiral diaphyseal radial fracture and a concurrent ulnar fracture. The reduction of the radius was near-anatomical (2° of both varus and recurvatum) with full restoration of normal radial length. The dog's fractures healed uneventfully by 70 days following surgery.[35] The clinical outcomes based on orthopedic examination, force plate analysis, goniometric and circumferential measurement of muscle mass evidenced slightly decreased range of motion in the ipsilateral elbow and carpus and mild brachial muscular atrophy. None of these alterations affected limb function, which was deemed excellent.[35]

3.3 | Femoral fractures

The femur, because of the abundant musculature, is perhaps the most challenging appendicular long bone to stabilize via MIPO. A modified lateral approach to the greater trochanter and proximal femur is used to develop the proximal plate insertional incision.[22,46] Proper plate contouring is necessary for restoring frontal plane alignment.[33] Obtaining proper torsional alignment is often more challenging. During fracture reduction, alignment is assessed with fluoroscopy, by palpating of the orientation of the femoral head and neck relative to the femoral condyles and using the location of the crest of origin of the vastus lateralis in relation to the femoral trochlea ridges.

In a prospective clinical study, Cabassu reported on the results of 20 femoral fractures stabilized using MIPO, 12 of which utilized a plate-rod construct.[33] Fluoroscopy was not used during these procedures, and two fractures required immediate surgical revision, both due to improper intramedullary pin placement. There was a statistically significant mean decrease in length (2%) and procurvatum (6°) of the stabilized femurs compared to the contralateral intact femur. Femoral neck version and frontal plane alignment did not differ from the contralateral femur. No information regarding time to osseous union or clinical outcomes was available for this study.[33]

A novel minimally invasive fracture reduction system has been recently developed and assessed in an in vitro experimental study.[47] The Sirius minimally invasive bone reduction handle system utilizes a pair of modified Kern bone holding forceps with extended handles to grasp and manipulate the major proximal and distal fracture segments. Once the major segments are aligned, a double external fixator connecting clamp is attached to the extension on each bone holding forceps and a connecting rod is secured by the clamps to maintain fracture reduction. Application of the Sirius minimally invasive bone reduction handle system resulted in a smaller final fracture gap when compared to using Kern bone holding forceps alone for fracture reduction in a synthetic femur with a long oblique fracture.[47]

3.4 | Tibial fractures

Schmökel et al.'s original description of MIPO in dogs reported the application in two tibial fractures, both of which obtained radiographic union without complications (Figure 1).[48] Schmökel et al. subsequently reported the results of tibial MIPO fracture repairs in six dogs and four cats.[49] In both case series, appropriate plate contouring facilitated acceptable reduction and alignment.[48,49] The only complications described were loosening of a screw in one case, which progressed to union without intervention, and 15° of torsional malalignment of the distal limb in one dog. Time to osseous union ranged from 35 to 42 days. All animals returned to full limb function by 90 days following surgery. Long-term follow-up had a mean time of 1140 days and revealed good to excellent use of the operated limb based on owners' feedback.[49]

Four additional studies have been published regarding outcomes of MIPO tibial fracture stabilizations in small animals.[31,33–35] Guiot and Déjardin published a prospective

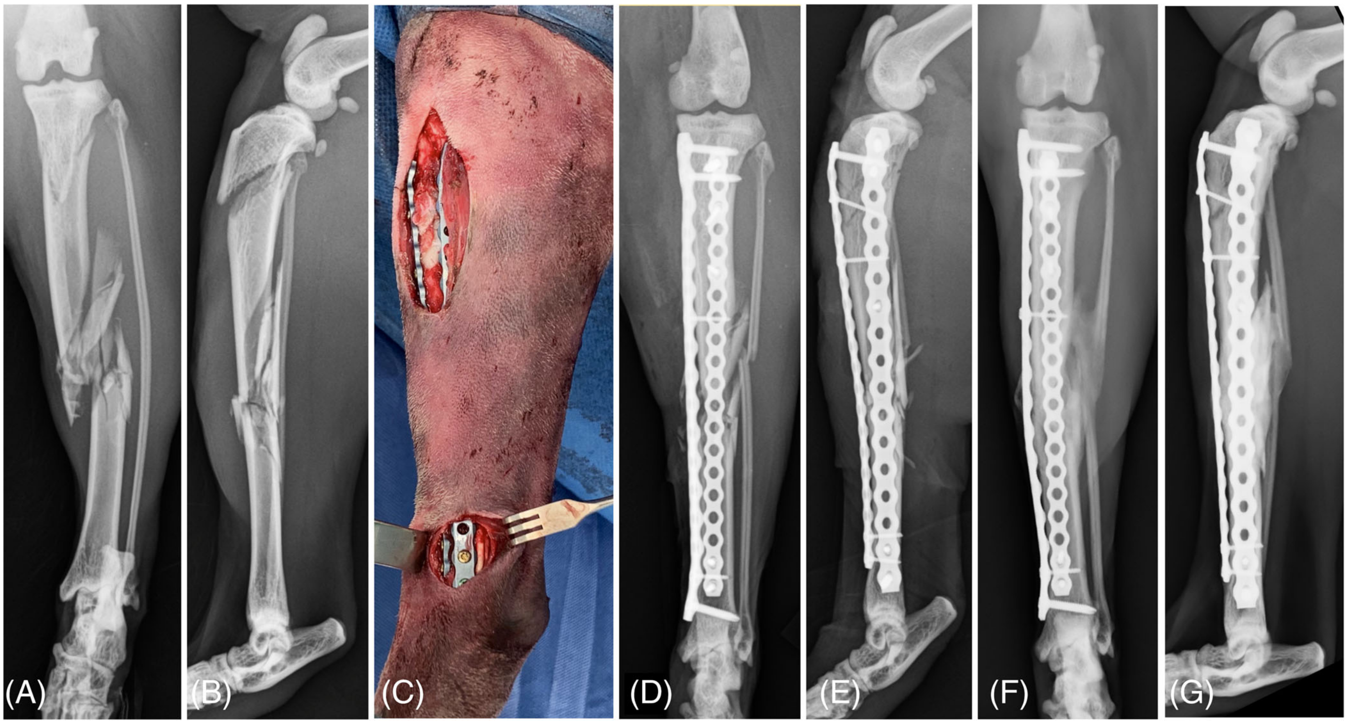

FIGURE 1 Minimally invasive plate osteosynthesis of a tibia fracture. Preoperative radiographs of the right tibia and fibula of a 6-year-old, male castrated, European shorthair cat with a closed, comminuted, mid-diaphyseal fracture and proximal metaphyseal, simple oblique fracture (A, B). Intraoperative photograph showing the proximal skin incision used for open reduction and fixation of the simple metaphyseal fracture and for the percutaneous insertion of the plates (C). A smaller distal incision was used for screw placement in the medial and cranial plates. Postoperative radiographs after repair using orthogonal plates (D, E). The proximal metaphyseal fracture was also stabilized with a lag screw placed through the third hole of the cranial plate. Follow-up radiographs 8 weeks after surgery (F, G). The fracture has healed. Mild valgus malalignment due to plate bending was noted. The cat returned to full function

study evaluating MIPO of tibial fractures in 28 dogs and 8 cats. Reduction and alignment were facilitated by use of a hanging limb technique, normograde intramedullary pin placement, and/or appropriate plate contouring. Postoperative frontal and sagittal plane alignment were similar to contralateral tibiae.[31] Rotational alignment was deemed as anatomical or near-anatomical in all cases. Mean ± SD for clinical union was 45 ± 21 days (range, 14–95 days). No additional clinical outcomes were specified, except for owner phone interviews done for six patients that did not return for scheduled radiographic recheck.

Boero Baroncelli et al. reported the results of a retrospective case series evaluating eight dogs which underwent MIPO tibial fracture repairs and compared outcomes to a case-matched cohort control group of dogs which had tibial fractures stabilized with plates applied via open reduction.[34] Reduction in these dogs was achieved using skeletal traction applied using a traction bow or a two-ring circular construct as well as appropriate plate contouring. Frontal and sagittal plane alignment of dogs treated with MIPO did not differ from repaired fractures in the control group and torsional alignment was deemed acceptable in all dogs. Clinical union was achieved at 30 days in 5/8 dogs in the MIPO group, but only 2/8 dogs in the open plating group. All of the fractures, except one stabilized via open plating, had obtained union at 60 days. Based on clinical examinations, all dogs in the MIPO group had obtained excellent limb function without signs of lameness when evaluated 30 days after surgery, while dogs in the open reduction group had only obtained a good limb function at the same time period.[34]

Townsend and Lewis used the Minimally Invasive Reduction Instrumentation System (DePuy Synthes Trauma) to facilitate MIPO stabilization of tibial fractures in two dogs.[35] These dogs had 3° or less procurvatum and varus and less than 2% discrepancy in length compared to the contralateral tibiae. One dog suffered implant failure within a week of surgery. The implants were removed and the fracture was restabilized again using MIPO and the Minimally Invasive Reduction Instrumentation System; there was 3° of valgus and 5° of recurvatum with 1% tibial shortening following revision.[35] The clinical outcomes were deemed excellent at time of final clinical recheck (median: 237 days; range, 92–238 days) based on orthopedic examination, force plate analysis, and goniometric and circumferential measurement of muscle mass.[35]

Cabassu prospectively evaluated efficiency of MIPO to stabilize tibial fractures without the use of intraoperative fluoroscopy in 13 dogs and 8 cats.[33] Alignment was assessed intraoperatively by palpation and clinical evaluation of the plane motion of the adjacent joints.[33] Based on postoperative radiographs, 14% of tibial fractures needed immediate revision surgery for improper intramedullary pin placement, intra-articular screw placement, or sagittal malalignment. Postoperatively, tibiae were shortened by an average of 1.4% with only 1.1° change in the tibial plateau angle compared to the contralateral tibia. Both frontal plane and torsional alignment were not different between limbs.[33] Specific clinical outcome measures were reported in this study.

3.5 | Summary

Although the limited number of published cases is insufficient to draw strong evidence-based conclusions, initial experience substantiates that MIPO can be successfully used to stabilize both simple and complex diaphyseal fractures (Supplemental Material: Tables). Based on authors' experience, open reconstruction is generally preferred for simple fractures unless minimally displaced. Although rarely reported in the published reports, operative times in MIPO cases often exceed operative times with open plating; however, operative time is dependent on several factors, such as expertise of the surgeon and fracture severity. The published data on MIPO support a low incidence of intraoperative complications, corroborating the authors' perception that MIPO can be performed successfully with low morbidity, but requires substantial experience with internal, and possibly external, fixation as well as meticulous technique. Studies have substantiated acceptable postoperative alignment and appropriate stabilization of fractures, particularly when fluoroscopy was utilized.[31,32,34,36,37,42] Surprisingly, implant placement was more problematic than obtaining acceptable alignment in the one study in which intraoperative imaging was not utilized.[33]

While MIPO purportedly accelerates fracture healing[37] and several studies report mean times to union of 30–40 days, which would be considered rapid in adult dogs, two of the three studies comparing MIPO to open plating failed to substantiate a difference in time to union.[34,36] Failure to demonstrate a difference may depend on the limitations associated with the quantification of fracture healing. One prospective study that utilized ultrasound as an outcome measure to assess radial fracture healing found a significant increase in early callus formation when comparing MIPO to open plating.[37] Prior published studies have lacked objective functional and client-based outcome measures. In the authors' perception, dogs treated with MIPO have a faster and more complete return to function. Future studies should objectively assess functional outcomes (Supporting Information: Tables).

4 | MIO: SACROILIAC FRACTURE-LUXATIONS

Minimally invasive stabilization of sacroiliac fracture-luxations via fluoroscopic-guided closed reduction and percutaneous lag screw placement mitigates trauma and shortens surgical time (Figure 2).[50–55] Fluoroscopic guidance facilitates anatomical reduction of the sacroiliac joint and accurate screw placement into the sacral body through a keyhole surgical incision.[50–55]

Accurate screw placement is the primary advantage of MIO for sacroiliac luxations. Both Tomlinson and Tonks reported, in separate retrospective studies, satisfactory screw placement in all cases.[50,51] Tomlinson et al. reported optimal reduction of the sacroiliac joint in 9/13 cases.[50] The postoperative pelvic canal diameter ratio was significantly larger than the preoperative diameter. No screw loosening was observed. One cannulated screw bent in association with failure of a plate stabilizing a contralateral ilial fracture 3 weeks after surgery. Tonks et al. reviewed medical records of 24 dogs.[51] All screws were satisfactorily positioned in the sacral body. The mean screw depth-to-sacral width ratio exceeded 60%, and the mean percent reduction of the sacroiliac joint exceeded 90%. Pelvic canal diameter ratios were significantly higher postoperatively than preoperatively. Three cortical screws loosened and one cancellous screw broke.[51] No follow-up clinical outcomes were available for both studies.

In a retrospective study, Kim et al. described results of MIO sacroiliac luxation stabilization in seven dogs.[52] The mean surgery time for unilateral and bilateral sacroiliac joint luxation stabilization was 30 min and 68 min, respectively. Postoperative pelvic canal diameter ratios were normal in all dogs. All dogs were ambulatory within 1 week after surgery, with the mean time to ambulation being 5 days.[52]

The lack of a control population having sacroiliac fracture-luxations managed conservatively or stabilized in open fashion is the main limitation of the previously discussed studies.[50–52] The only study comparing MIO sacroiliac luxation stabilization to open reduction was reported by Rollins et al. which retrospectively evaluated 17 dogs and cats treated with MIO and 24 animals addressed via open reduction.[53] Four MIO cases required conversion to an open approach to obtain adequate reduction. Accurate screw placement in the sacral body was obtained in 14/24 openly reduced and 12/13 fluoroscopic-guided closed reducted fracture-luxations. Optimal screw depth-to-sacral width

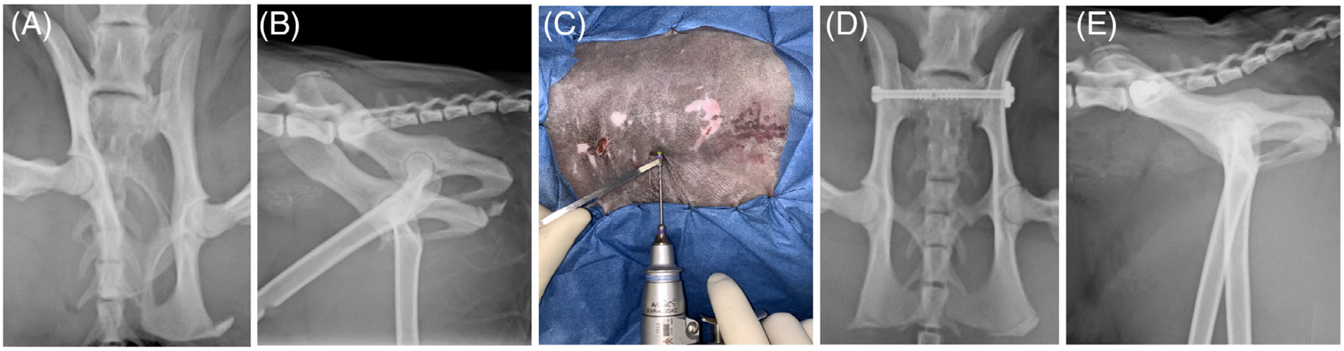

FIGURE 2 Minimally invasive osteosynthesis of a sacroiliac luxation. Preoperative radiographs of the pelvis of a 4-year-old, female castrated, European shorthair cat with bilateral sacroiliac joint luxation, diastasis of the pubic symphysis, and avulsion fracture of the ischial tuberosity (A, B). Intraoperative photograph showing drilling through a stab incision (C). On the left of the drill sleeve, a Kirschner is placed for temporary fixation. Postoperative radiographs after closed reduction and fluoroscopic-guided fixation of the sacroiliac luxation using two 2.4 mm cannulated screws (QuickFix, Arthrex, Naples, Florida) (D, E). Note the joint reduction, restoration of pelvic canal diameter, and correct placement of the screws into the sacral body

ratio was achieved more frequently in the fluoroscopic-guided closed reduction group (8/13 vs. 6/24). Optimal reduction was achieved less consistently in the closed reduction group (5/13) than in the open reduction group (13/24), but this difference was not statistically significant. Both methods were equally successful at restoring optimal pelvic canal diameter. Lag screw loosening was documented in 8/15 openly reduced fracture-luxations and only 1/12 closed reduced cases.[53] Objective outcome measures of functional recovery were not available.

Two ex vivo studies in dogs and cats demonstrated accurate sacral screw placement with the MIO technique.[54,55] Furthermore, a specific guide was described to facilitate accurate screw placement in a canine ex vivo study.[56] Leasure et al. described successful fluoroscopic assisted MIO sacroiliac luxation stabilization using a trans-ilial rod placed through the body of the sacrum in five dogs, which is most suitable for dogs with bilateral fracture-luxations.[57]

4.1 | Summary

The reported clinical results are excellent, with a low number of complications and a rapid return to function.[50–57] Although the only controlled study reported better anatomical reduction for the open technique,[53] the pelvic canal diameter was effectively restored in all cases.[52–57] In our experience, MIO is a viable technique, which typically yields anatomical reduction and fluoroscopic guidance facilitates accurate screw in the body of the sacrum.

Many sacroiliac-fracture luxations can be successfully stabilized with MIO, but case selection depends on the severity of displacement, the size of the animal, and chronicity of the injury. Reduction may be easier when the ilial wing has palpable instability. Chronic fracture-luxations may require open reduction. Obtaining accurate reduction is easier with unilateral fracture-luxations as the contralateral ilial wing is used to assess alignment. Placing screws in very small animals requires a high degree of precision.

5 | MIO FOR PHYSEAL FRACTURES

Mini-arthrotomy approaches, arthroscopic-assisted, or percutaneous osteosynthesis techniques have been described for the stabilization of physeal and articular fractures in dogs and cats (Figure 3). Many physeal fractures can be successfully managed with a MIO approach and several techniques have been described by various authors.[58–61] Indirect fracture reduction is performed by careful manipulation of the fracture fragments after distracting the fracture. Closed reduction has also been successfully facilitated by the application of a temporary two-ring circular fixator construct.[61] Percutaneous fixation is typically performed by placing interfragmentary Kirschner wires or small diameter Steinmann pins after confirming anatomical reduction with fluoroscopy or arthroscopy. Percutaneous needles are used to locate insertion points for wire or pin placement and implants are subsequently inserted under fluoroscopic guidance.

A retrospective study evaluated outcomes after closed reduction and fluoroscopic-assisted percutaneous pinning of 42 physeal fractures in 37 dogs and 4 cats.[58] All fractures were Salter-Harris type I or II injuries. Thirty-two physeal fractures were treated with cross-pinning and 10 with parallel pins. The mean operative time was 42 min. Minor complications occurred in one dog, while four dogs and one cat had major complications, including

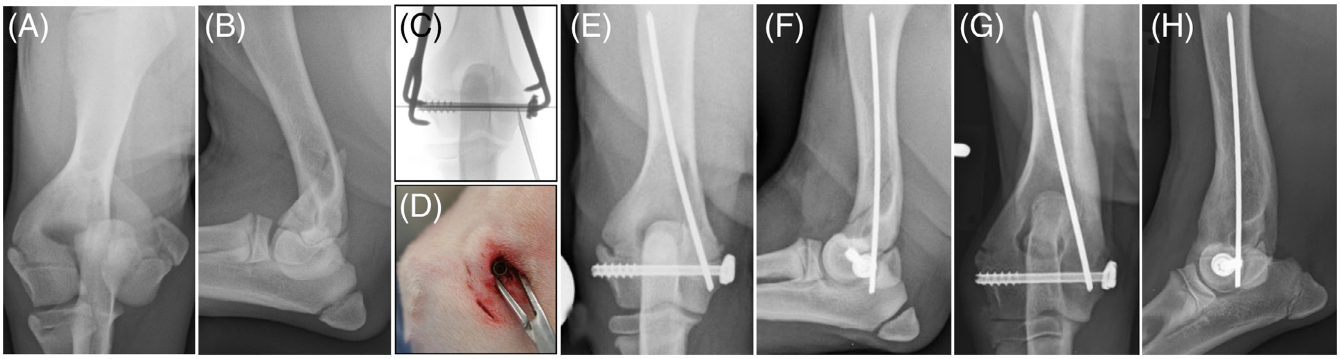

FIGURE 3 Minimally invasive osteosynthesis of an articular and physeal fracture. Preoperative radiographs of a 10-week-old, female intact, small Münsterlander dog, presented after falling from a height (A, B). A Salter-Harris type IV fracture of the medial aspect of the humeral condyle is visible, with caudolateral displacement of the medial fragment. Intraoperative fluoroscopic view of the elbow joint (C). After closed reduction with ligamentotaxis and finger manipulation, a Vulsellum forceps was applied and a needle was used to determine the correct position for the Kirschner wire insertion. Intraoperative photograph showing a small skin incision used to insert percutaneously the cannulated screw (D). Immediate postoperative radiographs showing excellent fracture reduction and satisfactory implant placement. (E, F) The transcondylar screw is close to the distal humeral growth plate and could have been placed 1 mm more distally. Follow-up radiographs obtained 4 weeks after surgery (G, H). The fracture has healed

infection, implant migration, or implant-associated soft tissue irritation requiring pin removal. Elective pin removal was performed in 41% fractures. Radiographic union was obtained in all 34 animals available for follow-up evaluations. Although nearly 80% of the animals had shortening of the fractured bone, greater than 90% of the animals had a full return of function. Eleven out of 41 animals had a comprehensive follow-up evaluation, including a clinical examination, radiographs of the contralateral limb, goniometric assessment of range of motion, and a validated questionnaire.

Hartman et al. reported a single case of a distal humeral Salter-Harris type II fracture in a 3-month-old German Shepherd treated successfully with percutaneous pinning. The fracture healed in 4 weeks and excellent long-term function was reported based on telephone interview and a validated questionnaire.[62]

von Pfeil et al. described percutaneous pinning for tibial physeal fractures in 14 dogs and 3 cats.[59] Intraoperative fluoroscopy or radiography was used in 11 tibial tuberosity avulsion fractures, one combined tibial tuberosity avulsion and proximal physeal fracture, and five distal tibial and fibular physeal fractures. Surgery times were <1 h. There were no intraoperative complications and reduction was deemed adequate in all cases. Implant removal was performed in 5/17 fractures. Complications consisted of pin-related soft tissue irritation, medial patellar luxation, and partial reavulsion of tibial tuberosity after stabilization. Final outcomes were judged as good in three and excellent in 14 cases. Follow-up clinical outcome measures included a clinical examination, validated owner questionnaire, and postoperative videos.

Several additional studies have substantiated the advantages for treating articular fractures with a minimally invasive approach.[63–66] The benefits afforded by the preservation of the soft tissues and avoiding a complete arthrotomy should not overshadow the principal priority when addressing articular fractures, which is obtaining stable, anatomical reduction.

Deneuche and Viguier described the successful MIO of a supraglenoid tuberosity avulsion fracture in a puppy.[63] The fracture was reduced and stabilized with a Kirschner wire and a cortical screw placed under arthroscopic guidance with nominal surgical trauma. Although incongruency of the articular surface was noted on postoperative radiographs, the dog had a rapid recovery with no lameness 28 days after surgery.

Unicondylar and bicondylar humeral fractures can be successfully stabilized using a MIO technique. Cook et al. published results of a prospective clinical study, in which 11 lateral humeral condylar fractures were reduced closed and stabilized with transcondylar screws and Kirschner wires under fluoroscopic guidance.[64] Anatomical fracture reduction was obtained in six fractures, while the remaining five fractures had <1.5 mm of articular incongruency. All fractures obtained union. The mean time of final follow-up examination was 445 days (range, 270–630 days), and all dogs regained excellent range of motion with a mean lameness score ranging from 0 to 1, based on a 5-point grading scale.

Au Yong et al. retrospectively evaluated the proficiency in performing closed, fluoroscopic-assisted reduction of 37 unicondylar humeral fractures in dogs.[65] Eleven of the 15 attempted closed reductions were successful. Fractures that were reduced and stabilized via closed reduction had a shorter time from injury to surgery. Closed reductions had significantly shorter surgical times compared with limited-open or open reductions. Twenty-one fractures healed without complications; four dogs developed minor postoperative complications: screw loosening ($n = 1$), Kirschner wire migration ($n = 2$), and persistent lameness ($n = 1$). Three fractures, all treated via open reduction, had major complications with loss of reduction and implant failure. Long-term follow-up data were obtained for 16 dogs via owner phone interview at a mean of 1200 days (range, 30–3840 days) following surgery. Fourteen out 16 owners contacted reported an excellent function of the operated limb.

Guiot et al. reported the results of MIPO stabilization of three bicondylar humeral fractures.[66] Percutaneously placed bone-holding forceps and normograde epicondylar pins were used to manipulate and anatomically reduce the humeral condylar fracture fragments. Following placement of a transcondylar screw, a bridging medial plate was applied from the proximal metaphysis to the humeral condyle, which spanned the portion of the fracture. Reduction was deemed to be satisfactory in all three dogs. Postoperative alignment was within 4° of the contralateral humerus. All three fractures healed within 42 days, and none of the dogs were lame at the last follow-up evaluation.

Grand described percutaneous screw fixation of incomplete ossification of the humeral condyle in four elbows.[67] All screws were successfully placed using an aiming device or under fluoroscopic guidance. No postoperative complications were observed, and no implants were removed. Two dogs had no lameness at final follow-up, while the dog that was operated bilaterally had persistent mild lameness. Similar results were reported in a retrospective study by Cinti et al., which reviewed the results of Kirschner wire stabilization of 35 physeal fractures of the capitulum of the humeral condyle in dogs, six of which were reduced in a closed fashion.[68] Complete functional recovery was observed in 31/35 fractures. At 28 days recheck, 27 of the dogs had complete clinical recovery with 0/5 lameness, five dogs had a 1/5 lameness, and one dog a 2/5 lameness.

Finally, closed reduction and MIO can be used for the treatment of carpal and tarsal bone fractures. Hudson and Pozzi described MIO fixation under fluoroscopic guidance to treat a central tarsal bone luxation in a dog, which resulted in a normal return to function.[69]

5.1 | Summary

Although the number of published reports is limited, the complication rate of physeal and articular fracture managed with MIO techniques appears comparable to or lower than reported with open techniques. Closed techniques are challenging and extensive prior experience with open reduction and fixation of physeal fractures is useful. Fluoroscopy and specific instrumentation such as cannulated drill bits and screws are advantageous. Fluoroscopy is recommended for assessing reduction and implant placement during surgery but can be unreliable for detecting minor incongruencies of the articular surface.[64,65,70] Arthroscopy is a more accurate modality for assessing articular surfaces, but the size of the joint can be a limitation. Newly available small diameter arthroscopes will likely broaden the spectrum of cases in which arthroscopic-assisted MIO can be performed.

While specific reduction devices are often used to perform MIPO, manual manipulation can yield successful reduction of Salter-Harris and articular fractures. Fracture fragments can often be aligned by ligamentotaxis. Distractive forces applied via the collateral ligaments and joint capsule (articular fractures) or the periosteum (physeal fractures) are used to mobilize fracture fragments. Fragments are then carefully palpated and reduced blindly. Reduction forceps can then be placed to maintain the reduction during implant placement.

A timely conversion to an open technique, reported in one study with a 30% incidence,[65] is critical to avoid prolonged surgical and anesthesia times. Conversion to an open technique can be minimized with appropriate case selection. The duration from injury and the degree of displacement influences the potential for indirect and anatomical reduction. Although these variables have not been investigated in prospective studies, the results of one retrospective study suggest that closed reduction of humeral condylar fractures is most likely to be successful if performed within 72 h of a dog sustaining the fracture.[59]

6 | CONCLUSION

MIO is an attractive alternative to open fracture-management. Improved biology should potentiate fracture healing with less resultant pain and a more rapid return to normal activity. Judicious analysis of the results of several large studies of human patients and the limited case series in dogs and cats, however, have yet to substantiate that MIO is clearly superior to open techniques.

The reports of MIO in dogs and cats provide evidence that MIO is feasible and can be performed with low complication rates, but this should be interpreted carefully because the published cases are often carefully selected and performed by experienced surgeons. As of yet we cannot conclude that MIO is superior to open fracture stabilization techniques based on the available evidence in veterinary literature. This conclusion is largely based on the perceived quality of the reported studies, which are often retrospective and lacking control groups, with small samples and limited outcome measures. Among the clinical studies on MIO reviewed here, less than 20% used objective measurements, such as force plate analysis, kinematics measurements, or validated owner questionnaire, to objectively substantial long-term clinical outcomes. The focus of most studies has been on reporting radiographic parameters such as postoperative alignment and fracture healing. The latter is often estimated based on large intervals between recheck examinations, which affords only an estimate of the time union. Unfortunately, functional outcomes are almost never included in the outcome assessment after MIO, but these parameters should be an important focus of future studies.

The objective of the review was to provide a realistic, updated summary of reports of MIO in dogs and cats and to stimulate future clinical research. In the authors' experience, MIO is a valuable modality that can be successfully performed in numerous traumatic fractures. MIO can deliver excellent outcomes when applied in carefully selected cases and performed by experienced MIO surgeons, but MIO should not be an excuse to accept poorly reduced and insufficiently stabilized fractures. Regardless of the approach, the basic principles of appropriate fracture management should be a priority for all trauma surgeons.

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CONFLICT OF INTEREST

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

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SUPPORTING INFORMATION

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