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CLINICAL RESEARCH

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Outcomes of 15 dogs and two cats with metabone fractures treated with fluoroscopically guided normograde metabone pinning

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Abstract

Objective: To report the outcomes of 15 dogs and two cats with metabone fractures treated with fluoroscopically guided normograde metabone pinning (FGNMP).

Study design: Retrospective case series.

Animals: A total of 15 client owned dogs and two cats with 57 metabone fractures.

Methods: Description of FGNMP and reporting of the following data: signalment, pre- and postoperative radiographs, intramedullary pin diameter used, anesthesia, surgery and coaptation times, duration to normal weightbearing and bone union, postoperative care and complications.

Results: Median surgery time was 54 min (range: 26–99), median duration of coaptation was 14 days (range: 1–5 weeks), median time to normal weight-bearing was 16 days (range: 2–45) and median time to bone union was 6 weeks (range: 4–12). All cases had at least 12 months of post-surgical follow-up with a median follow-up of 18 months (range: 12–70). No major complications occurred. Mild radiographic changes associated with subchondral bone sclerosis were noted on follow-up radiographs in 13/57 fractures. All cases returned to normal gait and full (15) or acceptable (2) function.

Conclusion: In this study, FGNMP was an effective and safe technique for metabone fracture repair, requiring only short-term external coaptation in most patients. Time to bone union and return to normal function compared favorably to previously reported techniques.

Clinical relevance: Fluoroscopically guided normograde metabone pinning provides an alternative technique for treatment of metabone fractures.

Abbreviation: FGNMP, fluoroscopically guided normograde metabone pinning.

1 | INTRODUCTION

Metabone fractures (MetaFx) are common in companion animals.[1–4] Surgery is recommended with fragment displacement >50%, when fractures are open, include the articular surfaces, the base of metabones II and V, the middle or distal metabone region, involve more than two metabones or metabones III and IV or MetaFx in working, sporting or show dogs.[1–4]

Crushing injuries are common and can seriously compromise the regional blood supply.[5]

Open reduction and internal fixation (ORIF) and application of bone plates or intramedullary dowel pinning may further impair the local blood supply and associated soft tissue.[6,7] Necrosis, malunion or delayed union, requirement for implant removal and complications associated with long-term postoperative coaptation are reported concerns.[2–4,6–10] Revision surgery rates with dowel pinning range between 0%[6,7] to 9.4%[2] and with bone plates from 22.5%[10] over 30.7%[9] up to 50%.[8]

Minimally invasive osteosynthesis (MIO) has many advantages over ORIF.[11,12] The need for additional surgery after MIO using external fixators (ESF), typically used in cases of open, comminuted or severely malaligned MetaFx, ranges between 0%[5,13–15] over 6.4%[10] to 33.3%[14] of cases.

The "support providing innovative dog equipment rehabilitation" (SPIDER) frame involves temporary percutaneous transarticular intramedullary MetaFx-pinning, with pin-ends connected externally using epoxy putty.[5] SPIDER produces good fracture alignment, but is beset by complications such as severe skin abrasions, high infection rates, paw distortion and constant lameness while the frame is in place.[5] Median time until frame removal was reported to be 32 days (dogs) and 46 days (cats); however, some patients had frames in place (which encroached metacarpophalangeal joints) for up to 9 weeks. Consequently, metacarpophalangeal osteoarthritis was reported in 54% of operated animals.[5]

Human MetaFx repair is performed by normograde pin placement directly via the metabone's articular surface, without incorporation into an ESF.[16–18] Despite metacarpal (MC) articular cartilage penetration, reports document high success and low complication rates.[16–18]

The purpose of this study was to develop, describe and retrospectively report the outcome and complications of fluoroscopically guided normograde metabone pinning (FGNMP) for MetaFx fixation in dogs and cats. Based on the high success rates reported in humans, we hypothesized that FGNMP would be associated with high success rates and low complication rates.

2 | MATERIALS AND METHODS

Records from dogs and cats undergoing FGNMP between January 2015 and June 2022, were reviewed. Surgeries were executed by four board-certified small animal surgeons with 1–7 years' experience as specialists before they performed their first FGNMP. Their median time of experience with intraoperative fluoroscopy was 2 years (range: 1–10). They were affiliated with Small Animal Surgery Locum PLLC, Friendship Surgical Specialists at Friendship Hospital for Animals, Sirius Veterinary Orthopedic Center and Veterinary Specialists of Alaska.

2.1 | Inclusion and exclusion criteria

Inclusion criteria were complete pre-, postoperative and follow-up radiographs (minimum duration of radiographic follow up: 4 weeks), medical records, data from lameness examination (lameness scores 0–5[19]) and physical examination by either a board-certified surgeon or primary care veterinarian, orthogonal radiographs of the operated region of interest, Liverpool Osteoarthritis in Dogs (LOAD) questionnaire[20] results or owner videos of the dogs or cats allowing gait assessment until at least 12 months postoperatively. Exclusion criteria were incomplete records or follow-up and dogs and cats with concurrent orthopedic injuries.

2.2 | Radiographic templating, pin selection, and intraoperative treatment decisions

Templating was performed using magnification recalibrated digital radiographs. Pre-operative pin selection aimed to achieve at least 70% medullary canal fill at the isthmus. The final pin-diameter was determined intraoperatively: prior to pin insertion, the chosen pin was placed over the fractured metabone and its diameter compared to the isthmus diameter of the inner metabone. Appropriate pin selection was possible because the outer and inner cortex of the metabones could be determined by appropriate adjustment of the fluoroscopy settings. A new pin was selected if necessary. If excessive resistance was felt during pin insertion, a smaller pin was chosen.

2.3 | Surgical technique

The hair on the affected limb was clipped to encompass the entire foot, including all interdigital hair, with margins extending proximally above the elbow or stifle. Thereafter, the foot was soaked in a 0.05% chlorhexidine solution for at least 10 min. This was done before standard aseptic skin preparation for surgery. The limb was positioned in dorsopalmar or dorsoplantar alignment relative to the fluoroscopy beam (Figure 1). In this position slight rotation of the foot and fluoroscope would allow for acquisition of fluoroscopic orthogonal views, while observing radiation safety protocols.[21] Correct positioning was assured prior to final aseptic preparation of the surgical site on the operating table (Figure 1).

A step-by-step guide to standard surgical technique as well as additional maneuvers, used if MetaFx reduction was challenging, are described within Boxes 1 and 2, and depicted in Figures 2–5. Postoperatively, a sterile dressing (Primapore Adhesive Wound Dressing Smith & Nephew, Fort Worth, Texas) was placed over the skin incisions and orthogonal radiographs were acquired. A splinted or soft-padded bandage was placed at the surgeon's discretion.

2.4 | Data recording

Information on the animal's breed, age, sex, medical history, physical examination findings, lameness score,[22] type of fracture and displacement of the fracture fragments (grade 1: <50% of the bone diameter; grade 2: 50%–100%; grade 3: >100%),[2] anesthesia and surgery times, pin diameters, postoperative care, follow-up plan and outcome[22] was recorded.

Postoperative radiographs were assessed for alignment, apposition and implant placement. Follow-up radiographs were assessed for evidence of bone union (callus bridging of at least three cortices),[23] malunion, delayed union, nonunion or synostosis. Radiographic changes of the metacarpo-/metatarsophalangeal joints were evaluated as absent (0), mild (1), moderate (3) or severe (4), as previously reported following MetaFx-treatment.[5]

2.5 | Acquisition of follow-up data

Clinical and radiographic data of all cases were recorded until bone healing was achieved.

All owners were asked to return for follow-up at least 6 months post-surgery. This request was made via email, text message and/or telephone calls. If there was no response after the sixth attempt to contact them, their pet was excluded from the study.

If follow-up with a board-certified surgeon was impossible, owners were offered a recheck with their local veterinarian, paid by the original surgical center.

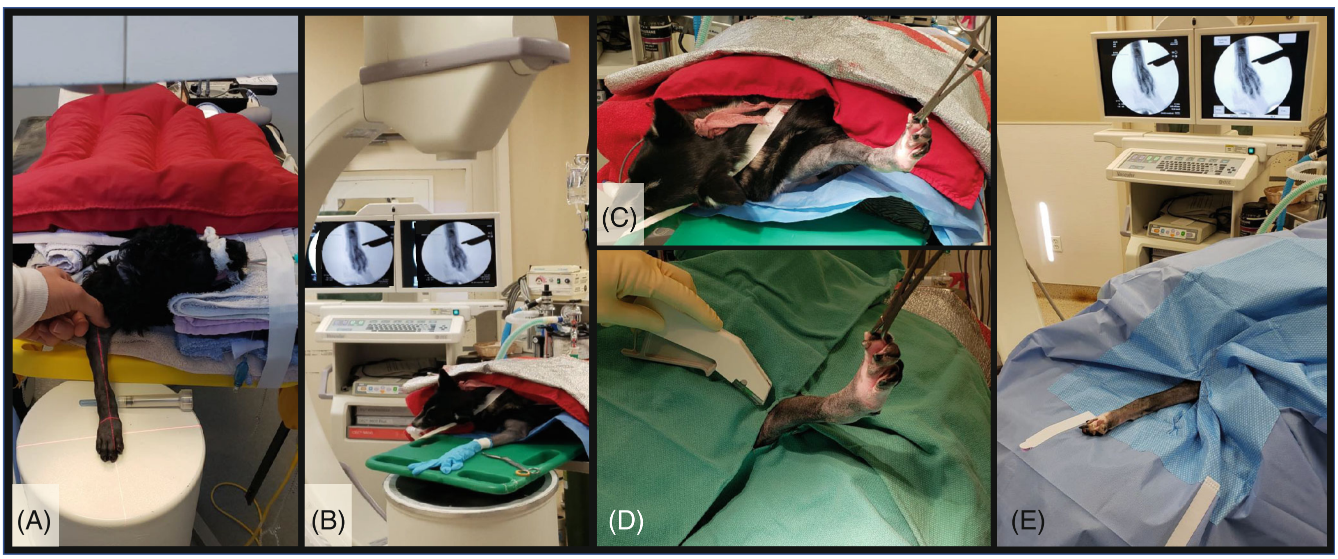

FIGURE 1 Patient set up, positioning and draping in two different patients (A, B–E). (A) Positioning before draping prior to fluoroscopically guided normograde metabone pinning (FGNMP)—The foot is directly aligned with the image intensifier, aided by a laser crosshair for precise centering of the area of interest. (B) Predraping paw covering—the paw remains protected within a 0.05% chlorhexidine-filled glove. The patient is positioned on a radiolucent board above the image intensifier. Scissors are utilized to ensure proper instrument and implant angling on the fluoroscopic screen before surgery commences. (C) Limb positioning during sterile preparation—a sterile Backhaus towel clamp is affixed to the toe. (D) Securing drapes—drapes are fastened in place using skin staples. (E) Completion of draping—the water-impervious drape is secured to the skin with additional skin staples, finalizing the sterile field.

BOX 1 Step-by-step surgical guide to fluoroscopic guided normograde metabone pinning (Figures 2–4)

- Hyperflex metacarpo-/metatarsophalangeal joint and place pin in the center of the head of the distal articular surface of the metabone in one of the following two ways:
  a. Percutaneously through digital extensor tendons (percutaneous technique) (Figure 2A).
  b. Through a small stab incision directly over the joint using a #11-blade and retracting the digital extensor tendons to the side with self-retaining Gelpi-retractors to expose the articular cartilage (Gelpi-technique) (Figure 3A).
- Attach an Allis, Kelly or Backhaus forceps to the nail of the fractured metabone to reduce risk of radiation exposure to the surgeon's hand and check appropriate pin placement with fluoroscopy (Figure 2B).
- Advance pin through distal metabone articular surface and into the medullary cavity of the distal fragment using an electrically powered pin driver (Figure 2C).
- Apply traction on forceps distally to reduce fracture under fluoroscopic guidance and advance pin normograde into the proximal fragment (Figure 4A).
- Drive pin to the metabone's base to predrill a path before being withdrawn approximately 10 mm (Figure 4B).
- Cut pin perpendicular to its axis as flush as possible with the joint surface (Figure 3B).
- Impact pins back into the medullary cavities using a K-wire-pin-punch (e.g., Veterinary Instrumentation, Sheffield or GerMedUSA, Garden City Park, New York) or a slightly larger pin, placed onto the distal pin-end (Figure 3C).
- Check pin countersunk below the articular cartilage visually if using Gelpi-technique (Figure 3D).
- Check final pin placement with fluoroscopy and manipulation of the metabone phalangeal joints through a full range of motion to ensure no crepitus (Figure 4C).
- Lavage surgical sites with sterile saline and close using intradermal absorbable monofilament suture or tissue glue (Figure 3E).

BOX 2 Trouble shooting maneuvers to achieve metabone fractures (MetaFx) alignment when reduction is challenging, followed by pin advancement into the proximal fragment (Figures 5, 6)

- Closed pin leverage:
  a. Retrieve pin tip to seat below the fracture line, adjust insertion angle (Figure 5).
  b. Pull digit distally and use pin-driver attached to the pin within the distal fragment for leverage (Figure 6A–C).
- Closed distal fragment manipulation: place small pointed bone reduction forceps or Backhaus towel-clamp percutaneously onto the distal fragment (Figure 6D, E).
- Open fragment manipulation through dorsal mini approach: use a Freer elevator, hemostat, or Kelly forceps to stabilize the proximal fragment and directly visualize pin placement (Figure 6F).
- If the above maneuvers are unsuccessful, if additional pin-placement is deemed unnecessary or if iatrogenic damage is of concern, leave MetaFx untreated (Figure 6G).

During that visit, a LOAD questionnaire was completed, a comprehensive examination was performed, focusing on detection of lameness and pain or crepitus during flexion, extension and rotation of the metacarpo-/metatarsophalangeal joints that had been accessed during FGNMP. Where possible, radiographs

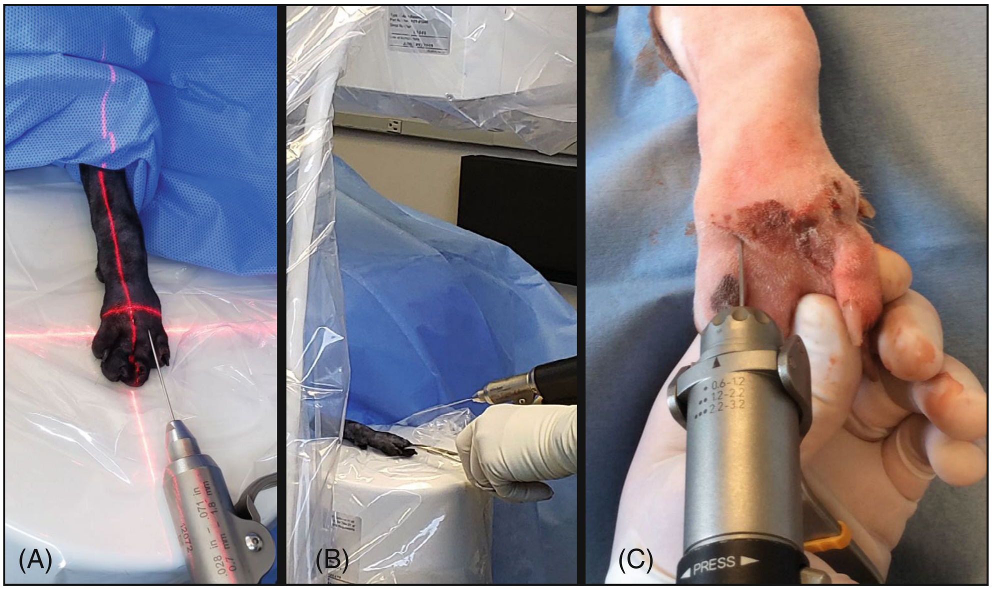

FIGURE 2 Intraoperative views of the percutaneous approach during fluoroscopically guided normograde metabone pinning (FGNMP). (A) Positioning of the pin over the metacarpophalangeal joint. (B) A Kelly tissue forceps is placed onto one toenail to allow traction, alignment and stability of the metabone fractures (MetaFx) fixation. (C) The metacarpophalangeal joint is flexed and the pin advanced through the articular surface into the distal metacarpal fragment.

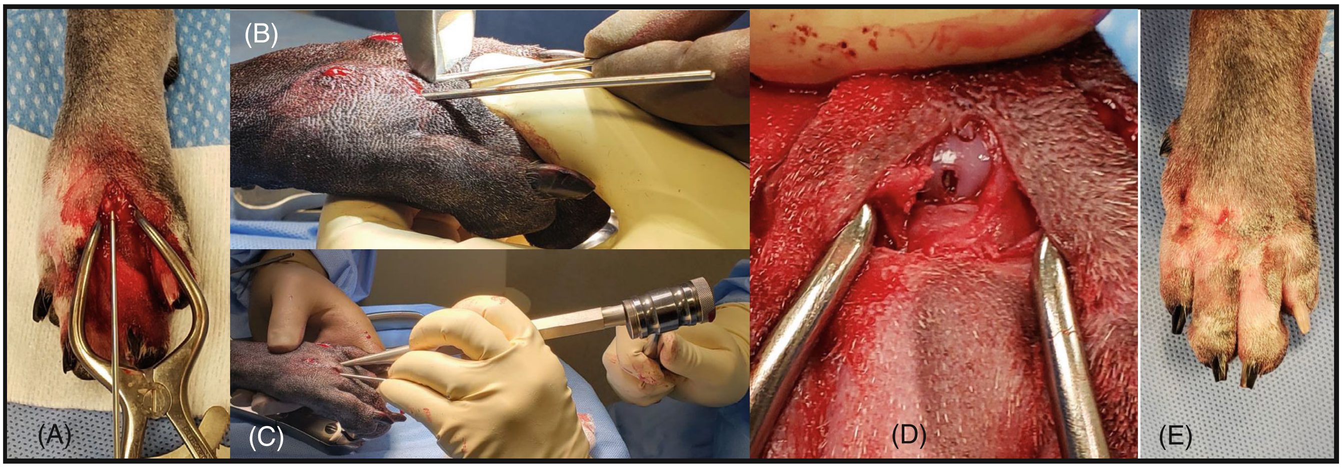

FIGURE 3 Intraoperative views of the Gelpi-technique during fluoroscopically guided normograde metabone pinning (FGNMP). (A) Gelpi retractor allows visual pin placement. (B) The pin is cut as flush as possible with the joint surface. (C) Pin-countersinking. (D) View of the countersunk pin. (E) Postsurgical view.

and videos of the animal's gait were obtained. If a direct examination was impossible, a single LOAD questionnaire and/or a video of the animal was obtained to assess quality of life and function.

All clients were contacted via telephone, at least 12 months post-surgery, to obtain final information on whether or not any changes had occurred since the last recheck examination and to complete a final LOAD questionnaire.

2.6 | Complications and outcome

Complications were defined as catastrophic, major or minor.[22] Final outcomes were defined as full, acceptable or unacceptable.[22]

3 | RESULTS

3.1 | Cases

Of 21 cases, 4 were excluded because of insufficient follow-up. Detailed data of the remaining 17 are available in Tables S1–S3 in Data S1. A total of 15 were dogs and 2 were cats. Median age was 6 months (range: 2–96). A total of 11 cases were under 12 months old (range: 3.5–9) and 6 were over 12 months old (range: 12–96). Median bodyweight for dogs was 12.5 kg (range: 1.8–32.1) and for cats it was 8.7 kg (range: 6–11.4). At initial presentation, 15/17 had a lameness score of 5/5 and two had a score of 4/5, with associated swelling and pain upon manipulation of the affected foot.

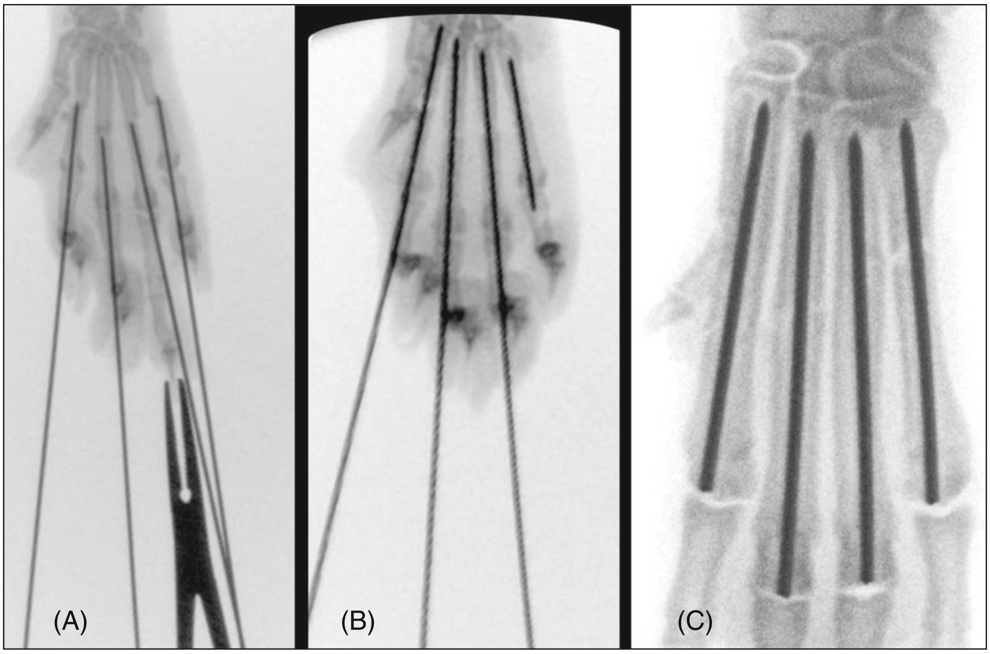

FIGURE 4 Fluoroscopic views. (A) Pins placed within the distal fragments; a Kelly tissue forceps is placed over the toe of digit IV to aid with fragment manipulation. (B) Pins advanced into the proximal fragments. (C) Pins countersunk below the articular surface.

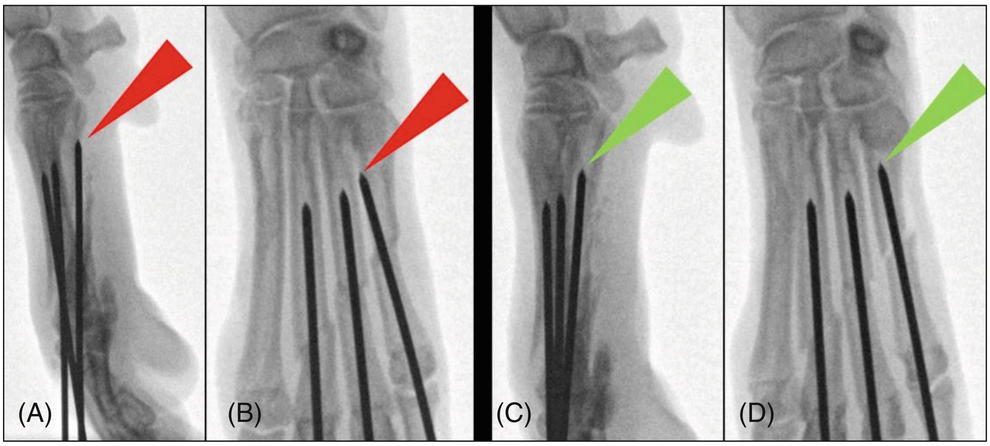

FIGURE 5 Orthogonal fluoroscopic images of an initially misplaced pin (A, B—red arrowheads) which was able to be corrected by readjusting prior to final normograde placement and countersinking (C, D—green arrowheads).

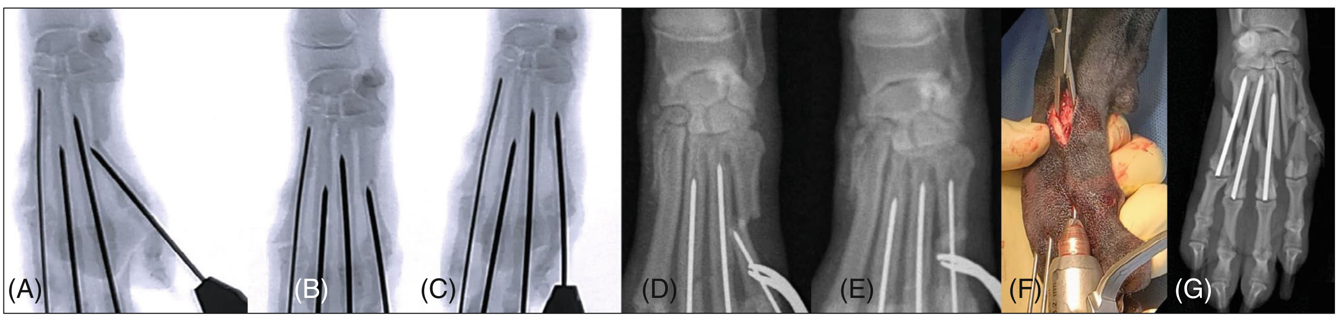

FIGURE 6 Techniques for managing challenging fragment reduction and fixation. (A–C) Pin-leverage technique using a pin-driver attached to the pin within the distal fragment while traction is applied the corresponding digit to align fracture. (D, E) A percutaneously placed Backhaus towel clamp is used to aid reduction. (F) Dorsal mini approach allowing stabilization of the proximal fragment using Kelly forceps and directly visualized pin placement. (G) Stabilization of only three out of four metabone fractures (MetaFx) when pin placement into MC II was not possible.

3.2 | Radiographic findings

Metacarpal (MC) and metatarsal (MT) fractures were recorded in 13 and 4 cases, respectively, totaling 64 closed MetaFx. Fracture configurations were short-oblique body (56), physeal (4) and comminuted (4). Grade I fragment displacement was found in 29, grade II in nine and grade III in 26 MetaFx. A total of 10 dogs had open metabone physes. One metatarsus showed a very small dorsal slab-fracture at its head (Table S1 in Data S1).

3.3 | Surgery and coaptation

Median anesthesia and surgery times were 177 min (range: 132–232) and 54 min (range: 26–99), respectively. Administration of anesthetic and postoperative medications varied (Table S2 in Data S1).

Successful completion of FGNMP was performed in 57/64 (89%) MetaFx in 17 cases. The percutaneous approach was used in 10 and the Gelpi-technique was used in 7 cases. All pins were documented by the surgeon to be countersunk below the articular cartilage surface intraoperatively.

Closed reduction and stabilization were achieved in 48/57 (84%) MetaFx without any additional approaches. Percutaneous placement of pointed reduction forceps was required in in 2 and a dorsal mini approach was required in 6 MetaFx to facilitate proper reduction. All those maneuvers were conducted by surgeons at the lower end of the experience spectrum in using intraoperative fluoroscopy. In one dog with metacarpal fractures, conversion from MIO to a limited open approach was necessary and the incision was extended to exceed 50% of the bone's length while FGNMP was performed. This was necessary to allow better pin placement and occurred during the initial learning curve of one of the surgeons. In that specific dog, a mesh-expansion of the regional skin was required following skin-closure to reduce skin-tension. Median pin diameter was 1.6 mm (range: 0.9–2.8).

Stabilization was not performed in a single MetaFx in seven individual cases due to failure of reduction (4), subjective concerns for splintering/fissuring due to brittle bone quality (2; case #2, an Italian Greyhound) and a Salter-Harris type I fracture assessed to be best treated conservatively (1).

Coaptation consisted of soft padded (14) or splinted (3) bandages.

3.4 | Peri- and postoperative care

Appropriate pre- intra- and postoperative medications were administered and patients were closely monitored during surgery (Table S2 in Data S1). Postoperative medications typically consisted of a combination of an antibiotic, analgesic, and anti-inflammatory for 3–14 days and a sedative as needed until bone union was evident radiographically. Specifics for postoperative care, duration of coaptation, restricted activity, time until follow-up radiographs and return to normal activity were recorded.

The median time of coaptation was 2 weeks (range: 1–6), with weekly bandage changes. Strict cage rest was mandatory for 4-8 weeks, depending on evidence of bone union on first follow-up radiographs and age of the animal, with younger animals undergoing a first recheck between 4-6 weeks. Dogs were allowed a maximum of 3 short (5–10 min) leash walks daily.

No running, jumping, playing or stair climbing was permitted until evidence of bone union was established. Thereafter, activity was limited to leash walks of up to 30 min (dogs) or free movement in a larger cage or small room (cats) over an additional period of 2–4 weeks. Then, normal activity resumed. Cats were kept crated until evidence of radiographic bone union was recorded.

3.5 | Postoperative radiographs

All postoperative radiographs of treated MetaFx showed appropriate fragment-alignment and apposition (Figures 6G, 7B, 10A). Median fill of the isthmus of the inner metabone was 96.5% (range: 68.4–100). Measurements were made for MC III on all cases with the exception of 1 dog, in which MC III was not pinned. Pin-tips extended beyond the base of the metabone proximally in 2 MetaFx. In a further 3 MetaFx, pin-tips extended proximally either medial or palmar/dorsal to the metabones. Pin extension beyond the subchondral bone of the distal metabones was noted radiographically in 24 (42%) MetaFx.

3.6 | Clinical follow-up

3.6.1 | Initial follow-up

All examinations were performed by a board-certified surgeon until radiographic union was confirmed.

Median lameness score 5 weeks after surgery (range: 4–8 weeks) was 0 (range: 0–2). Median time to normal weight bearing, as reported by owners, was 16 days (range: 2–45). Despite receiving instructions for a least 6 weeks' strict rest, some owners permitted their pets to resume unrestricted activity as early as 4 weeks postsurgery. Consequently, the median time to normal activity was 6 weeks (range: 4–8).

At the time of presentation for the initial radiographic examination, all previously fractured metabones were

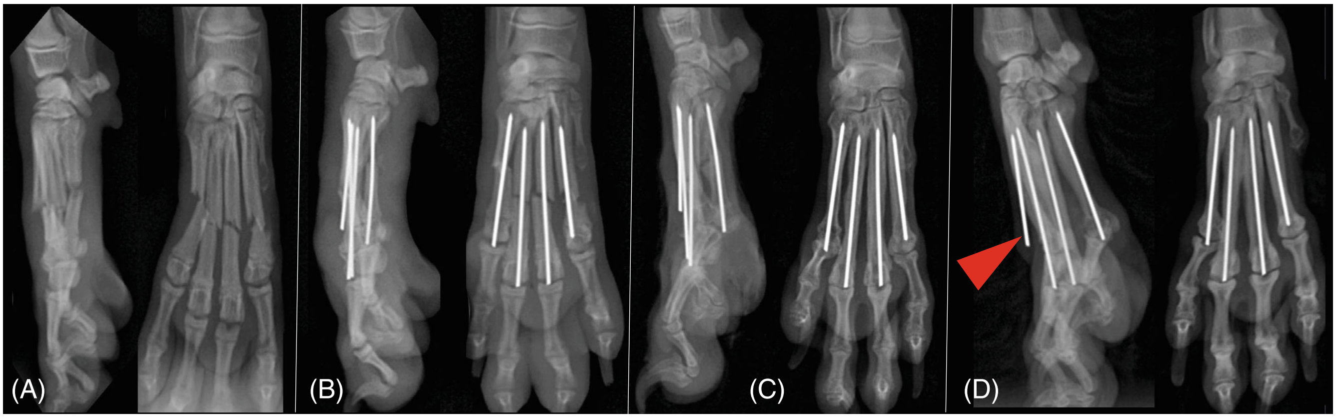

FIGURE 7 Radiographic series of metacarpal (MC) fractures from presurgery (A), to immediately postoperatively (B), 6 weeks postoperatively (C) and 14 months postoperatively. (D). Although the pin ends appear to be located within the metacarpophalangeal joints radiographically on digits 3, 4 and 5, these were confirmed to be seated below the articular surface at surgery and did not result in any radiographic signs of osteoarthritis 14 months postoperatively (D). Similarly, the location of the pin end dorsal to MC-II (red arrowhead) had no negative clinical impact.

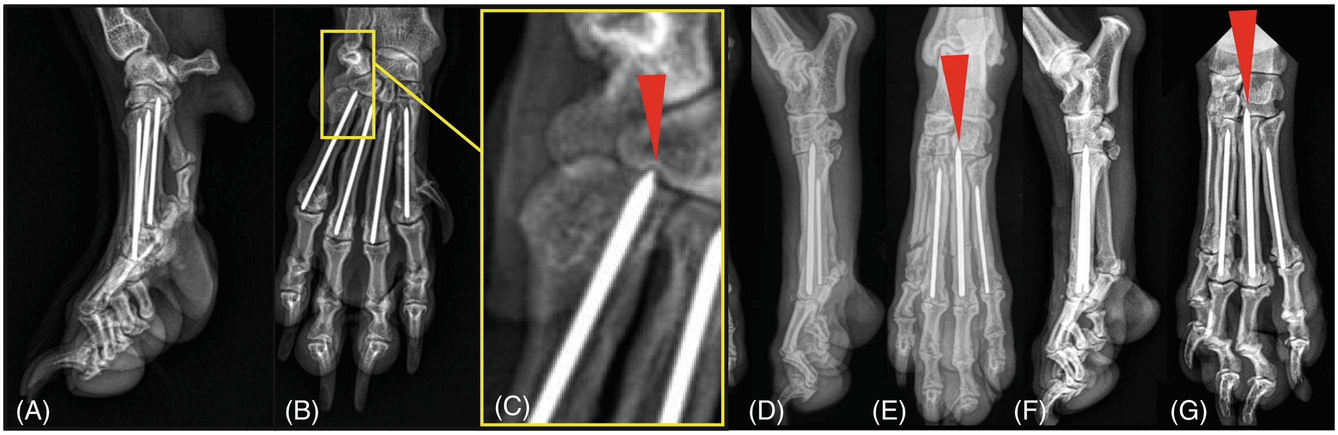

FIGURE 8 Long-term follow-up on two cases with proximal metacarpal/metatarsal (MC/MT) bone penetration: mild proximal penetration of MC V 5.7 years after surgery (A–C). The magnified view highlighted in yellow (C) shows a small area of radiolucency of carpal bone V associated with pin tip protrusion (red arrowhead), potentially an Überschwinger effect. (D–G) Proximal pin protrusion into the tarso-metatarsal joint 3.6 years after surgery with no signs of irritation. Neither case was associated with discomfort on manipulation or lameness.

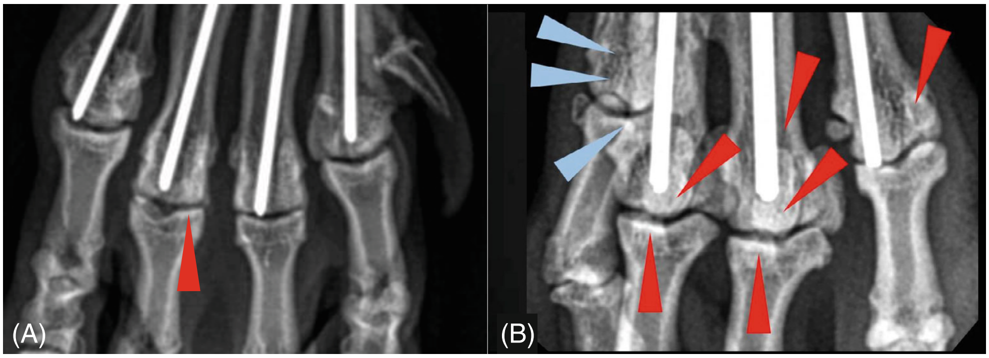

FIGURE 9 Sclerotic changes in two cases at long-term follow-up: mild sclerosis at the medial aspect of the proximal phalanx (red arrowhead) 5.7 years post-surgery (A) and mild subchondral bone sclerosis, with irregular appearance of the distal metatarsal (MT) and intramedullary radiolucency (red arrowheads) 3.6 years post-surgery (B). Note that there were similar changes in the nontreated MT (blue arrowheads). Neither case was associated with lameness or discomfort on manipulation of the metacarpophalangeal joints.

palpated. The pressure applied caused the surgeon's fingertips to turn white. In addition, all metabone/phalangeal joints were flexed, extended and rotated, resembling a standard orthopedic examination. Although no pain response occurred during metabone palpation, examining 4 metabone/phalangeal joints in 4 different dogs resulted in mild limb retraction without vocalization, akin to a dog resistant to toenail cutting but permitting foot examination.

Eleven out of 17 cases (43/64 overall; 43/57 FGNMP-treated MetaFx) showed bone union at this time. Additional radiographic follow-up was performed in the remaining 64 cases at a median of 2.8 weeks (range: 2–6) later. None of those cases showed any lameness.

Median time to radiographic bone union in all FGNMP-treated metabones was 6 weeks (range: 4–12). Two MetaFx that were not pinned showed mild malunion and one developed nonunion. Neither was documented to have lameness or discomfort on palpation.

A pressure sore was documented at the olecranon in one case at 6 weeks post-surgery. The bandage had been extended proximal to the elbow based on the preference of the attending surgeon. The sore healed without additional treatment after bandage removal.

3.6.2 | Medium- to long-term follow-up

For 11 cases (42 FGNMP-treated MetaFx), an additional direct follow-up physical examination was performed by a board-certified surgeon (8) or referring veterinarian (3) at a median of 12 months (range: 6–64) post-surgery. None of those dogs showed lameness or pain upon examination. One dog had mild medial rotation, and slightly longer toenails of MC III and IV when compared to the other two nails.

Radiographic follow-up of the metabones treated via FGNMP (pinned metabones) (Figures 7–10) revealed the following mild abnormalities: synostosis between neighboring metabones (3), mild lucency around the proximal pin-tip in carpal bone II (1), mild lucency around the distal pin-tip (3) and minimal pin bending (1). Overall, mild radiographic changes of the metacarpo-/metatarsophalangeal joints were found in 7/42. Those included: subchondral bone sclerosis of the distal metabone or proximal phalanx (4), irregular bone appearance of the distal metabone (3). Interestingly, some of those changes were also seen in nonaffected metabones (Figure 9 and Table S3 in Data S1). Pin migration was not observed in any case.

In nonpinned metabones, radiographic abnormalities included: malunion (2), nonunion (1), synostosis between neighboring metabones (1), irregular bone appearance of the distal metabone (1), progressive growth of the dorsal MC slab-fragment, which had been identified on pre-treatment radiographs, leading to mild regional soft-tissue swelling and mild irregularities around the corresponding MT-phalangeal sesamoid bone (1). None of those radiographic abnormalities had any impact on clinical function and there was no pain upon direct palpation, flexion, extension and rotation of the treated metabones and the metabone-phalangeal joints.

In the remaining 6 cases contacted at that time, follow-up was obtained via telephone/Email/LOAD questionnaire/videos at a median of 23 months (range: 7–58). Those animals could not return for a direct examination and radiographs due to travel distance (3) or concerns related to stress for the animal (3).

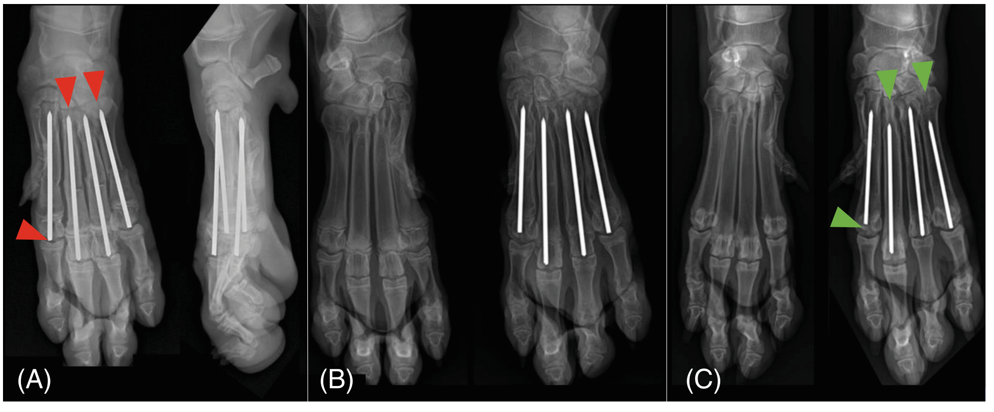

FIGURE 10 Radiographic progression of physeal growth following fluoroscopically guided normograde metabone pinning (FGNMP) of metacarpal (MC) fractures in an immature dog. (A) Immediate postoperative radiographs. Red arrowheads indicate pin ends in respect to neighboring joint spaces. (B) One month postoperative radiograph compared with the contralateral metabones. (C) Nine months postoperative radiograph alongside contralateral foot showing continued physeal growth. Note the distances from pin ends to the joint spaces (green arrow heads), when compared to (A), indicating continued longitudinal metabone growth after FGNMP.

LOAD questionnaires completed at this medium to long-term follow-up from all 17 owners revealed a median score of 0 (range: 0–8). All cases were considered to have achieved full function at that time.

3.6.3 | Final follow-up

Final telephone follow-up was performed at a median of 18 months (range: 12–70) post-surgery. LOAD questionnaires of all 17 cases revealed a median score of 0 (range: 0–7). Owners reported continued full functional outcome in 15 cases. Acceptable function was found in two dogs with recurrent mild lameness (grades 1–2/5) following prolonged high-impact activity, although in both cases, this would resolve without medical treatment within 24 h. One of those dogs had a distodorsal slab-fracture of either MC III or IV preoperatively and developed mild regional soft tissue swelling in that area at the medium-term follow-up. Radiographs of the other dog did not reveal signs of osteophytosis at the metabone/phalangeal joints, but synostosis between MC III and IV. Clinical impact of those findings was unclear.

4 | DISCUSSION

This study on 57 MetaFx undergoing FGNMP indicates the technique is feasible, allows appropriate fragment alignment, apposition and pin-placement is associated with a quick recovery. A total of 15 cases achieved full and 2 cases achieved acceptable functional outcome.[22]

Although this was not a comparative study between various techniques to treat MetaFx, there are numerous perceived benefits associated with FGNMP. The soft tissue sparing effect related to the MIO-approach is the biggest advantage when compared to bone plates or dowel-pinning. In addition, FGNMP can be used for various fracture configurations especially as pin length can be chosen to span the entire metabone, requires only a short period of coaptation and is associated with fast bone healing and return to normal function. As pin ends are seated below the articular cartilage, there is no implant-associated intra-articular wear, which is of concern when using the SPIDER-technique;[5] there are none of the concerns often encountered with external fixation[24] and there is no need for planned implant removal. While no case in this series was affected from chronic nonunion secondary to instability, FGNMP might also be applied to such scenarios and could be assessed in future studies.

Preoperative planning and intraoperative fluoroscopic assessment help select the most appropriate pin diameter. Previous publications described pin sizes for metabones of between 0.6 and 1 mm,[6,7] but if the medullary cavity allows, larger pins should be used. In this study, the range of pin diameter was 0.9–2.8 mm and a median canal fill 96.5% was achieved, exceeding the general recommendations of approximately 70% for intramedullary pins,[25] suggested to increase bending resistance. Indeed, as the area moment of inertia increases with the fourth power of the pin diameter and since the former is a crucial factor for construct stiffness,[26] larger pin diameters provide greater resistance to bending and deformation. Conversely, metabone-splintering while inserting too large a pin must be avoided.[6] One option to minimize this risk would be retrograde pin-placement from the fracture site, advancing the pin through the distal metacarpo-/metatarsophalangeal joint and completing the procedure as described for FGNMP. While this would ensure optimal pin diameter and centralized pin placement, the small open approach to the fracture site may potentially result in loss of the benefits associated with MIO.[11,12]

Development of metacarpophalangeal osteoarthritis is reported to occur in 54% of dogs operated on following the SPIDER-technique,[5] mild radiographic changes of the metacarpo-/metatarsophalangeal joints were found in 7/42 (16.7%) of our cases (Figure 9) and following dowel pinning, the incidence osteoarthritis is reported to be 3%.[2] All of those have in common that, despite the noted radiographic changes, no negative clinical impact was reported. Similarly, no concerning signs from osteoarthritis are reported following normograde pinning across the distal metabone's cartilage to treat phalangeal-metacarpal luxations with temporarily placed pins[27] and metacarpal fractures with variations of ESF.[5,28] Finally, temporary transarticular pinning of the elbow[29] and coxofemoral joints[30] and retrograde pin placement via the femoral weightbearing articular surface[31] in small animals is not reported to result in clinical signs of osteoarthritis.

In humans, retrograde interlocking nailing through the femoral articular cartilage,[32] but more importantly, transarticular intramedullary metacarpal pinning and headless screw placement,[16–18,33] have not been shown to cause osteoarthritis. This is particularly significant because osteoarthritis of the human fingers would likely have made these techniques[35] obsolete, given the importance of finger function.

Regardless, minimizing iatrogenic arthritis secondary to FGNMP should be a goal, which is achieved by adequately seating the pin ends below the articular surface, as confirmed intraoperatively. It is crucial to create a sufficiently long pilot channel within the proximal epiphysis. This is because if the pin is cut too long, it will be difficult to countersink and may not be able to be advanced past the proximal end of the medullary cavity of the metabone. Although some postoperative radiographs appeared to demonstrate pin extension beyond the subchondral bone, there was no crepitus or pain on manipulation and these were confirmed intraoperatively to have been countersunk below the level of the articular cartilage. Given the thickness of the cartilage of the metabones and minimal radiographic metacarpo-/metatarsophalangeal joint changes seen on radiographic follow-up, it is likely these pins are seated within the radiolucent articular cartilage. Therefore, FGNMP appears safe from major risk for permanent joint damage. We believe that the articular cartilage defect is quickly covered with fibrocartilage, allowing early function and minimizing negative clinical long-term effects, but histological study would be needed to support this theory. In the current study, while medium to long-term radiographs revealed mild changes around the distal metabones, osteophytes within the metacarpo-/metatarsophalangeal joints were not seen, gait was normal and direct examination of the metabone/phalangeal joints did not reveal pain in any case. Rare penetration of the proximal metabone's cortex did not seem to result in clinical or radiographic concerns; an area of mild radiolucency around the proximal pin tip in one case (Figure 7) might potentially represent an Überschwinger effect.[34]

The reported median time for post-surgical coaptation after MetaFx-repair via ORIF is 7.5 weeks (range: 5–10).[1,2,6–8,35] In contrast, we placed bandages for a median of 2 weeks, mainly to reduce swelling rather than to increase stability. This minimized the need for rechecks and reduced costs. While bandage-associated complications are frequent[2,6–8] and are reported in 1 study to occur in up to 34% post MetaFx-repair,[10] only 1/17 (5.9%) of our cases developed a pressure sore over the elbow (the one dog who only received two pins and had a mesh extension). We believe that the substantial canal fill in each metabone, as discussed above, and use of multiple pins create a biomechanically stable environment. This, coupled with early weightbearing on a foot that is bandaged only for a short period of time, is believed to contribute to expedited bone healing. According to our findings, bandaging beyond 2 weeks following FGNMP is likely unnecessary when treating at least 3 of the 4 metabones. As of the current writing, this represents the shortest reported recommendation for coaptation following any method of MetaFx-repair fixation.

The median times of cage rest, controlled increase of activity and return to normal activity in our cases were all overall also shorter than in previous reports.[1,2,5–7,10] Although early weightbearing following pin placement has not been advocated previously, it is possible that this in combination with the advantages of MIO resulted in the quick recovery and bone union in our cases.

Notably, some owners disregarded discharge instructions and allowed an earlier return to normal activity. Therefore, the median time to normal function was recorded at 6 weeks. While deviating from the author's recommended postoperative protocol is not advised, it is possible that these unintended findings can be attributed to the minimally invasive approach and biomechanical advantages of utilizing multiple pins for treating fractures of multiple metabones.

However, other factors likely also contributed to those shorter times, namely less severe injuries and fracture patterns, no open fractures and more dogs than cats as in other publications.[2,6,7,14,15] Indeed, injuries of cases treated with the SPIDER technique[5] occurred secondary to direct crushing or bending impact, resulting in highly comminuted fractures, more cats than dogs were treated and the average age of treated animals was 10 months. In contrast, our study showed mainly simple diaphyseal fractures, more dogs than cats were included and 11/17 cases were 12 months old or younger (median age: 6 months). Only a prospective, randomized study comparing the different techniques in a large group of patients will be able to provide an answer on the optimal treatment for MetaFx.

Similar to a study in growing children undergoing intramedullary pinning for MetaFx that crossed the physes,[36] we did not observe a negative impact on limb- or joint-function following FGNMP in immature dogs (Figure 10). Pins crossed the physes at a perpendicular angle, as recommended.[37] However, most of those cases approached skeletal maturity or were small breeds with minimal expected additional growth. Thus, the precise impact on physeal function following FGNMP is unclear.

Osteomyelitis is reported to have developed in 2% of 176 cases undergoing "dowel-pining."[2,6,7] Although not detected in our study, osteomyelitis would be a significant concern, as pin removal would be challenging and invasive. It would be necessary to use a high-speed burr to access the pin, cut it, then remove it. However, as FGNMP is a MIO-technique, shown to reduce infections compared to ORIF[11,12] and osteomyelitis has not been reported following percutaneous pinning of other fractures in small animals,[38–40] it is possible that the risk for this complication with FGNMP is small. Standard aseptic procedures were applied, encompassing the preparation of the limb from the digits to the elbow or stifle, respectively. This included preoperative soaking of the foot in a disinfectant, for example, 1.2% chlorhexidine diacetate,[41] as described in this study. Wrapping the pads and toenails with sterile covers could also be considered, but was not done in our cases. Infected or open MetaFx were not treated by FGNMP.

Malunion or delayed union following metabone fracture has previously been reported to occur at a median of 21.6% (range: 0–66) of cases.[2,5–7,9,10,13–15] Overall, there is a trend that this appears more frequent following treatment solely by external coaptation, when not all metabones were surgically stabilized[2,6–9] or when treated by external fixation.[10,14,15]

In contrast, all FGNMP-treated cases healed rapidly, while bone healing problems only occurred in untreated MetaFx. Malunion of nonpinned MetaFx occurred in a dog in which FGNMP was limited to MC II and V, while III and IV were left untreated because the surgeon had concerns, that pin-placement could result in iatrogenic metabone splintering due to subjective assessment of bone being too brittle. Despite these changes, there was no long-term impairment of gait nor discomfort of any joint in this dog. This case highlights the importance of performing FGNMP on all MetaFx, whenever possible, to reduce the chance of complications. Whilst a single pin in one metabone is unable to withstand shear, rotation and bending forces across all metabones, the authors believe that following FGNMP of all MetaFxs, the entire foot becomes a biomechanically superior construct.

Synostoses between metabones following ORIF are reported to occur at a median of 22.7% (range: 20–71.2),[2,6,7,9] which is similar to 3/17 dogs (17.6%) in our study. This could be explained by the MIO-approach taken during FGNMP compared to ORIF. Similar to previous reports,[2,6,7] synostoses did not appear to result in lameness, with exception of possibly 1 dog, reported to have mild lameness after excessive exercise, who developed synostosis between MC III and IV.

The follow-up in our cases (12–70 months) was longer than other reports (4–15 months).[2,5–8] Long-term lameness following conservative or ORIF-treatment of Metafx is described in 3%–73% of cases.[2,8,9] In our cases, a recurring, mild lameness was observed subsequent to extended periods of high-impact activity, affecting 2/17 dogs (12%). Notably, this lameness spontaneously resolved without any intervention within a single day.

Study limitations include low case numbers, missing long-term radiographs, possible bias toward owner-assessed outcomes or surgeon-bias and lack of computerized gait analysis. Fluoroscopy is costly, requires special training and radiation safety remains a concern. Despite using fluoroscopy, additional steps had to be taken in 16% to achieve optimal pin placement. It is noteworthy that all of these maneuvers were carried out by surgeons with relatively limited experience in utilizing intraoperative fluoroscopy. As indicated by additional experience in FGNMP (unpublished data from the authors), the need for performing supplementary steps diminishes over time. Drawing solely from our experience with alternative techniques and their documented descriptions in the literature, it is posited that the mini approach employed in some of our cases is presumed to be less invasive and having a more sparing impact on regional soft tissues when compared to other methods. However, as our study did not involve methods such as angiography, post-surgical anatomic dissection or histopathology, we cannot comment on actual differences in vascular compromise in our cases post-injury and post-treatment and how those differ from other techniques. Nevertheless, it is widely acknowledged in numerous publications that one of the primary advantages of MIO is its soft tissue-sparing effect.[42] While a comparative study would be necessary to provide scientific evidence, we believe that any of the previously reported ORIF approaches, regardless of whether plates or dowels are used, may lead to more regional soft tissue damage. This assertion, although not empirically proven in our study, is consistent with the recognized benefits of MIO.[11,12] Although those trouble shooting maneuvers did not seem to impair bone healing, the effect of those maneuvers on regional blood supply is topic of future investigation.

Although bone union was assessed using 3-cortex healing, due to the superimposition of multiple bones in the mediolateral plane, this was at times difficult or impossible. However, not all radiographs showed complete superimposition of all bones, as shown for example in Figures 7, 8 and 10, allowing adequate bone healing assessment.

The LOAD questionnaire was developed to compare dogs prior to and after a certain treatment, for example whether or not a certain anti-inflammatory improves signs of arthritis.[20] In contrast, we used LOAD to assess function only at medium to long-term as well at final follow-up, similar to other studies.[43–45] LOAD questionnaire data was not collected at first presentation as all dogs showed severe lameness.

Our results demonstrate that FGNMP is an effective and safe treatment for a variety of MetaFx configurations in dogs and cats. FGNMP requires only a short period of coaptation postoperatively and is associated with quick recovery, bone healing and good to excellent long-term outcomes.

AUTHOR CONTRIBUTIONS

von Pfeil, D, J. F, Dr.med.vet, DVM, DACVS (Small Animal), DECVS, DACVSMR, DECVSMR, ACVS Founding Fellow MIS (Small Animal Orthopedics): Invented the technique, contributed to the design of the study, identified suitable medical records, recorded demographic information, compiled all data, performed radiographic measurements, interpreted data, drafted, revised and brought the manuscript to completion in cooperation with all other authors. Tan D, BVSc (Hons), DACVS (Small Animal), Adams R, BVM&S, MRCVS, DECVS and Glassman M, VMD, DACVS (Small Animal): Significantly contributed to the study by providing cases, interpreting data and revising the manuscript. All authors provided a critical review of the manuscript and endorsed the final version. All authors are aware of their respective contributions and have confidence in the integrity of all contributions.

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no financial interests.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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