Assessment of fracture healing after minimally invasive plate osteosynthesis or open reduction and internal fixation of coexisting radius and ulna fractures in dogs via ultrasonography and radiography

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Objectives—To evaluate fracture healing after minimally invasive plate osteosynthesis (MIPO) or open reduction and internal fixation (ORIF) of coexisting radius and ulna fractures in dogs via ultrasonography and radiography.

Design—Prospective cohort study.

Animals—16 dogs with radius-ulna fractures that underwent MIPO (n = 9; 2 dogs were subsequently not included in the analyses because of incomplete follow-up information) or ORIF (7).

Procedures—Dogs in the 2 treatment groups were matched by age, body weight, and configuration of the fractures. Fracture healing was evaluated with ultrasonography, power Doppler ultrasonography, and radiography every 3 to 4 weeks until healing was complete; a semiquantitative score based on the number of Doppler signals was used to characterize neovascularization, and subjective B-mode ultrasonographic and radiographic scores were assigned to classify healing.

Results—Fractures in dogs that underwent MIPO healed in significantly less time than did fractures in dogs that underwent ORIF (mean ± SD; 30 ± 10.5 days and 64 ± 10.1 days, respectively). Radiography revealed that fractures in dogs that underwent MIPO healed with significantly more callus formation than did fractures in dogs that underwent ORIF. Although Doppler ultrasonography revealed abundant vascularization in fractures that were healing following MIPO, no significant difference in neovascularization scores was found between groups.

Conclusions and Clinical Relevance—For dogs with radius-ulna fractures, data indicated that bridging osteosynthesis combined with a minimally invasive approach contributed to rapid healing after MIPO. The MIPO technique may offer some clinical advantage over ORIF, given that complete radius-ulna fracture healing was achieved in a shorter time with MIPO. (J Am Vet Med Assoc 2012;241:744–753)

Abbreviations

MIPO Minimally invasive plate osteosynthesis
ORIF Open reduction and internal fixation

The concept of biological osteosynthesis refers to the preservation of the blood supply to a bone during surgical fixation of a fracture to ensure early bone healing with reduced risk of complications. In biological osteosynthesis, the major fracture segments are aligned in a functional position without surgical exposure via indirect reduction or, if exposure is necessary, with an open-but-do-not-touch technique. With this method, the fracture hematoma and the periosteal soft tissues are minimally disturbed. Benefits of biological osteosynthesis can result in reduced operative time, reduced need for bone grafting, and more rapid union.

Recently, a new method of bone plating has been developed that allows application of a plate through small incisions made remote to the fracture site. Percutaneous plating or MIPO involves the application of a bone plate, typically in a bridging fashion, without making an extensive surgical approach to expose the fracture site. After reducing the bone segments with indirect reduction techniques, small plate insertion incisions are made at each end of the fractured bone and an epiperiosteal tunnel is made connecting those incisions. The plate is inserted through one of the insertion incisions and tunneled along the periosteal surface of the bone, spanning the fracture site. This technique conforms to the principles of biological osteosynthesis because the fracture site is not exposed and the fracture hematoma is only minimally disturbed.

Biological osteosynthesis has rarely been compared with anatomic reconstruction. Dudley et al compared open reduction and bone plate stabilization with closed reduction and external fixation of comminuted fractures.
tibial fractures in dogs. No significant difference in healing time was found between treatment groups, but fewer major complications developed in the closed reduction group. In another study, fragment reconstruction and bone plate fixation was compared with bridging plate fixation for repair of highly comminuted femoral fractures in dogs. Surgical times were shorter and healing occurred more rapidly in the dogs treated with bridging plate fixation, but no significant differences in complication rate were noted between treatment groups. In dogs with diaphyseal fractures, biological fixation was compared with anatomic reconstruction by use of interlocking nails. In that study, fractures in dogs treated with biological fixation healed in a shorter time and the dogs were able to bear weight on the affected limb sooner, compared with findings for dogs treated with anatomic reconstruction. Similar results would be expected in a comparative study of dogs with fractures that underwent MIPO or ORIF because percutaneous application of a plate entails the principles of biological osteosynthesis. To the authors’ knowledge, no studies have been performed to date that compare healing patterns and interval to union achieved via the MIPO and ORIF techniques in dogs with fractures.

Bone healing can be evaluated with several imaging techniques, including radiography, cross-sectional imaging (ultrasonography, CT, and MRI), or scintigraphy. Although radiographic examination is still the most widely used method to quantify bone healing, radiography lacks the ability to evaluate the soft tissue around the fracture, which is especially important during the development of a soft tissue callus in secondary bone healing. Results of previous studies have indicated that ultrasonography is a sensitive and accurate means for detection of early fracture healing in diaphyseal fractures of long bones in clinical patients. Additionally, the use of power Doppler ultrasonography has been used to estimate the vascularity at the fracture site. Vascularization develops in the soft tissues surrounding the fracture site as early as 4 days after surgery and extends into the soft tissue callus during the early stages of fracture healing. Conversely, in directly apposed and rigidly affixed fractures, detection of power Doppler signals at the fracture site is comparatively delayed after surgery and the signals are located only at the bony surface. In comparison, radiographic diagnosis of fracture healing depends on visualization of mineralized tissue at the fracture site during secondary fracture healing, which involves bridging of the fracture site with iso-opaque callus. Therefore, radiographic assessment of fracture healing may lag behind the actual stage of healing and clinical stability at the fracture site.

The purpose of the study reported here was to evaluate the time from treatment to complete fracture healing as determined by use of ultrasonography and radiography and to describe the healing pattern on the basis of ultrasonographic and radiographic examination results in dogs with coexisting radius and ulna fractures repaired with the MIPO or ORIF technique. We hypothesized that fractures repaired via MIPO would heal faster than fractures repaired via ORIF. We also hypothesized that vascularization at the fracture site after MIPO would develop earlier and to a greater extent, compared with findings after ORIF.

Materials and Methods

Study design—Dogs that had simple, closed fractures of both the radius and ulna of 1 limb caused by a single traumatic incident, which were to be stabilized with MIPO or ORIF techniques, were eligible for inclusion in the study (Figures 1 and 2). Dogs with open or comminuted fractures or dogs undergoing revision surgery or requiring postoperative external coaptation were excluded from the study. Prospective data were gathered from 14 dogs, and data from 2 dogs were included retrospectively; 2 dogs that underwent MIPO were subsequently not included in the analyses because of incomplete follow-up information. To compare the treatment groups, the cases in each group were matched by age (in months) and body weight (in kg). Type of fracture was also controlled by including only dogs with simple fractures of the radius and ulna of 1 limb. Dogs for which follow-up (radiographic or ultrasonographic examination) was incomplete and dogs that did not meet the inclusion criteria were not eligible for participation in the study.

Information regarding signalment, body weight, cause of fracture, concurrent musculoskeletal injuries, and interval between time of injury and surgery was recorded for each dog. The dogs were evaluated at the time of surgery and at 3- to 4-week intervals after surgery or until healing as determined by ultrasonography.
SMALL ANIMALS

approach were performed as previously described of the patients. A bone graft was not used in any 2.7-mm veterinary cuttable plates, and 2.0-mm dynam plates, 2.7-mm dynamic compression plates, 2.0- to plates and limited compression-dynamic compression were selected at the surgeon’s discretion. Plates used of the plate and the number and position of the screws fixation was performed with an open approach, direct reduction, and application of plate and screws accord

Surgical technique—Open reduction and internal fixation was performed with an open approach, direct reduction, and application of plate and screws according to the AO manual of fracture management. Length of the plate and the number and position of the screws were selected at the surgeon’s discretion. Plates used in the study included 3.5-mm dynamic compression plates and limited compression-dynamic compression plates, 2.7-mm dynamic compression plates, 2.0- to 2.7-mm veterinary cuttable plates, and 2.0-mm dynamic compression plates. A bone graft was not used in any of the patients.

For the MIPO group, the surgical preparation and approach were performed as previously described; some data from 3 dogs in the MIPO group in the present study have been reported. Briefly, indirect reduction was achieved with a single-block circular fixator, which also allowed maintenance of the reduction during plate application. After realignment of the fracture fragments, an MIPO approach to the radius was performed as described. After creating a proximal and a distal insertion incision, Metzenbaum scissors were used to create an epiperiosteal tunnel. Use of periosteal elevators was avoided because of the risk of iatrogenic damage to the periosteum, unless deemed necessary in small dogs. The plate was inserted through the insertion incisions and fixed with a minimum of 2 screws/fragment. Additional screws were placed through stab incisions, if necessary.

Ultrasonography—For each dog, ultrasonography of the affected forelimb was performed at all follow-up examinations until complete healing was evident via both ultrasonography and radiography. A linear transducer (L15-7 MHz or L17-5 MHz) equipped with spatial compounding was used for the ultrasonographic examinations. Circumferential B-mode ultrasonographic examinations in longitudinal and transverse planes were used for morphological assessment of the callus and fracture site as well as for assessment of the implant-bone interface. Power Doppler examination of the fracture site was performed to assess vascularization. Still images and cine loops were stored on a picture archiving and communication system in Digital Imaging and Communications in Medicine (DICOM) format for assessment at a later date. B-mode images were used to determine the stage of healing based on the echogenicity and organization of the tissue at the fracture site. Fractures in stage 5 were considered healed. Time to union was recorded as the interval time between completion of surgery and the follow-up examination at which the fracture was considered to be at stage 5.

Vascularization in the region of each fracture was evaluated on the still images available and assessed qualitatively and quantitatively via reported methods. A qualitative description of the localization of vascularization was recorded for 4 locations as follows: soft tissue immediately surrounding the fracture, bone surface exposed along the fractured ends of the bones, callus, and a combination of soft tissue and bone surface (Appendix 1). For quantitative analysis, vascularization was assigned a grade on the basis of the mean of the number of Doppler signals at all sites combined as follows: grade 0, 0 Doppler signals; grade 1, 0 to < 5 Doppler signals (red or purple); grade 2, 5 to < 10 Doppler signals (orange); and grade 3, > 10 Doppler signals (yellow).

Radiography—For each dog, 2 standard radiographic views were obtained before surgery, immediately after surgery, and at each subsequent follow-up examination until complete healing was evident via both ultrasonography and radiography. Immature dogs were followed up at 2 weeks after surgery in addition to the monthly scheduled follow-up examinations.

A radiographic scoring system, adopted from Whelan et al., was used to grade the progression of fracture healing at the follow-up examinations (Appendix 2). For each dog at each time point, the 2 radiographic views were assessed for callus formation, appearance of the fracture line, and stage of union; on the basis of those findings, a fracture healing grade of 1 to 5 was assigned to each radiographic view and a
Whitney test. For all statistical analyses performed, a value of P < 0.05 was considered significant.

Implant information was reported as plate length and plate working length. Plate length was expressed as the total number of screw holes of the plate. Plate working length was considered as the distance between the innermost screws and was reported as the number of empty holes. The fracture gap was measured on the cranio-caudal radiographic views and defined as the mean distance between the medial and lateral cortices of the fracture ends. The total plate length (represented by the total number of screw holes of the plate) is 11, and the working length (the distance between the innermost screws; reported as the number of empty holes) is 6. By use of a radiographic scoring system (in which a fracture healing grade of 1 through 5 was assigned on the basis of callus formation, appearance of the fracture line, and stage of union), fracture healing immediately after MIPO was assessed as grade 5 (indicative of no healing and nonunion). R = Right.

Animals—Sixteen dogs were enrolled in the study; 2 dogs that underwent MIPO were subsequently not included in the analyses because of incomplete follow-up information. There were 7 dogs in each treatment group. For the dogs that underwent MIPO, mean ± SD body weight was 6.7 ± 3.9 kg (14.7 ± 8.6 lb). For the dogs that underwent ORIF, mean age was 24.1 ± 14.7 months and mean body weight was 6.0 ± 4.6 kg (13.2 ± 10.1 lb).

In all dogs, the MIPO or ORIF procedure was performed successfully. For dogs that underwent MIPO, mean plate length (number of holes) was 10.7 ± 2.4 and plate working length (number of holes in which a screw was not placed) was 4.3 ± 1.6 (Figure 3). For dogs that underwent ORIF, mean plate length (number of holes) was 8.0 ± 1.2 and plate working length (number of empty holes) was 0.3 ± 0.8 (Figure 4). All dogs underwent 2 or 3 postoperative follow-up examinations. The first postoperative follow-up examination was performed 2 weeks after surgery in immature dogs and 4 weeks after surgery in mature dogs. Of the 7 dogs that underwent MIPO, 3 were immature. Of the 7 dogs that underwent ORIF, 3 were immature. For dogs that underwent MIPO or ORIF, no complications associated with the implants were detected at any time point.

Ultrasoundographic findings in dogs that underwent MIPO—The mean ± SD values of stage of healing determined (with consideration of location of vascularization) via ultrasonography and mean power Doppler scores (indicative of extent of vascularization in the re-
Table 1—Stage of fracture healing (assessed via ultrasonography), power Doppler score for vascularization, and grade of fracture healing (assessed via radiography) at 3 to 4 weeks after surgery in dogs that underwent MIPO (n = 7) or ORIF (7) for treatment of simple, closed fractures of both the radius and ulna in 1 limb.

<table>
<thead>
<tr>
<th>Variable</th>
<th>MIPO</th>
<th>ORIF</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage of fracture healing determined via ultrasonography*</td>
<td>3.9 ± 0.9</td>
<td>2.6 ± 0.9</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Power Doppler score for vascularization†</td>
<td>1.8 ± 1.3</td>
<td>0.6 ± 0.5</td>
<td>0.20</td>
</tr>
<tr>
<td>Grade of fracture healing determined via radiography‡</td>
<td>2.1 ± 1.1</td>
<td>3.4 ± 0.5</td>
<td>&lt; 0.05</td>
</tr>
</tbody>
</table>

The P values apply to the comparison of a given variable between treatment groups; a value of P < 0.005 was considered significant.

*Stage of fracture healing (stages 1 through 5 where stage 1 is no signs of healing and stage 5 is signs of complete healing) was determined via ultrasonography on the basis of the echogenicity and organization of the tissue at the fracture site and localization of neovascularization. †Vascularization was assigned a grade on the basis of the mean of the number of Doppler signals from all assessed sites of 1 patient at 1 visit as follows: grade 0, 0 Doppler signals; grade 1, 1 to 5 Doppler signals (red or purple); grade 2, 5 to 10 Doppler signals (orange); and grade 3, > 10 Doppler signals (yellow). ‡Grade of fracture healing (in which a fracture healing score of 1 through 5 was assigned on the basis of callus formation, appearance of the fracture line, and stage of union) was determined via a radiographic scoring system (grade 5 is indicative of no healing and nonunion).

At this time point, radiographic grade of healing was 5 in all dogs.

The mean value of radiographic grade of healing at the first postoperative follow-up examination was calculated for dogs that underwent MIPO (Table 1). Morphologically, callus formation in the fracture gap was observed via B-mode grayscale ultrasonography (Figure 5); the callus extended superficial to the bony surface in all dogs at this time point. Ultrasonographic healing stage ranged from 3 to 5. Five of the 7 dogs had a hyperechoic callus with acoustic shadowing at the first follow-up examination (range, 27 to 48 days). In 2 dogs, a hypoechoic callus was noted at the first follow-up examination, which indicated ongoing but not complete secondary fracture healing. Both of these dogs had achieved complete union at the time of the second follow-up examination (42 and 61 days for these 2 dogs).

Power Doppler scores for vascularization ranged from 0 to 3 at the time of the first follow-up examination (Table 1). Vascularization was abundantly present within the callus and surrounding soft tissues in nonhealed fractures (n = 4) at the first follow-up examination (Figure 5). In the remaining 3 dogs, the fractures had healed and either vascularization was absent (n = 2) or a minimal amount of vascularization was seen only at the bony surface (1). Vascularization scores were 1 and 3 for the 2 dogs that had a second ultrasonographic follow-up examination (Figure 6); fractures in these dogs were completely healed at the time of the second follow-up examination.

Radiographic findings in dogs that underwent MIPO—Immediately after surgery, the mean ± SD fracture gap measured on the craniodorsal radiographic views was 2.6 ± 1.3 mm for dogs that underwent MIPO. At this time point, radiographic grade of healing was 5 in all dogs.

The mean value of radiographic grade of healing at the first postoperative follow-up examination was calculated for dogs that underwent MIPO (Table 1). At the first follow-up examination (range, 27 to 48 days), 3 fractures had healed; grades ranged from 1 to 4 for all 7 dogs (Figure 5). At the time of the second follow-up examination...
(range, 42 to 61 days), all fractures had healed; radiographic grades of healing were 1 or 2 (Figure 6).

Ultrasoundographic findings in dogs that underwent ORIF—A minimal amount of callus formation was evident in the fracture gap at all ultrasoundographic follow-up examinations in the dogs that underwent ORIF (Figures 7 and 8). Stage of healing determined (with consideration of location of vascularization) via ultrasonography at the first follow-up examination ranged from 2 to 5 (range, 18 to 45 days). Fractures in 3 dogs were classified as healed at this time.

Power Doppler scores for vascularization were 0 or 1 in all 7 dogs that underwent ORIF at the time of the first follow-up examination (Table 1; Figures 7 and 8). A low number of power Doppler signals were seen at the bony surface in 5 dogs at the first follow-up examination. In the 2 dogs for which no vascularization was detected, the fracture in one was healed and the fracture in the other was not healed (ultrasoundographic stage, 2). The fracture in the latter dog was healed at the third follow-up examination (12 weeks after surgery).

Radiographic findings in dogs that underwent ORIF—Immediately after surgery, the mean fracture gap measured on the craniocaudal radiographic views was < 1 mm in all dogs that underwent ORIF. At this time point, the radiographic grade of healing was 5 for all dogs that underwent ORIF. Radiographically, no fractures had healed at the time of the first follow-up examination (18 to 45 days after surgery); grades were 3 or 4 for all 7 dogs (Figure 7). However, at the time of the second follow-up examination (range, 36 to 80 days), all fractures had healed; radiographic grades of healing were 1 or 2 (Figure 8).
Mean time to union—Mean time to union determined via ultrasonography or via radiography for the 2 treatment groups was compared. Via ultrasonography, time to union was 26.4 ± 10.9 days and 37.0 ± 19.6 days in the MIPO and ORIF treatment groups, respectively; this difference was significant (P < 0.05). Via radiography, time to union was 30.0 ± 10.5 days and 64.0 ± 10.1 days in the MIPO and ORIF treatment groups, respectively; this difference was significant (P < 0.05).

Discussion

In the present study, simple, closed radius-ulna fractures in most dogs that underwent MIPO healed in < 4 weeks, whereas fractures in dogs that underwent ORIF healed in approximately 8 weeks. The healing pattern revealed via ultrasonography and radiography in the MIPO group was consistent with secondary bone healing, characterized by richly vascularized callus developing at the fracture site. Regardless of the plating technique used, fractures in all dogs healed uneventfully in < 12 weeks.

In another study, in dogs, vascularization (characterized via ultrasonography) during long bone fracture healing after closed application of external fixator (n = 32) and after ORIF (15) was compared. The ultrasonographic findings indicated that there was a time-dependent development and regression of vascularization at the fracture site, which was more evident in the external fixator treatment group. In that group, a larger number of Doppler signals with a concurrent increase in combined vessel area or measured Doppler signal area peripheral to the cortex was detected in the early stages, with a peak between 11 and 20 days after treatment. In the later stages of healing, the quantity and vessel area of the signals decreased, until they were only found at the surface of the callus, and ultimately disappeared. This pattern of healing is similar to the pattern detected in dogs that underwent MIPO in the present study. At the first follow-up examination, the fractures in most dogs in the MIPO treatment group were healed or had a greater power Doppler score for vascularization, compared with findings in dogs in the ORIF treatment group, confirming the hypothesis that MIPO allowed more rapid healing with greater vascularization than did ORIF. Conversely, in the dogs that underwent ORIF, callus was either not evident or was apparent only 8 weeks after fixation. This finding was not unexpected because callus formation is the hallmark of secondary bone healing, which occurs in conditions of relative stability of the implant-bone construct. Despite the different ultrasonographic and radiographic patterns of healing between groups in the present study, there was no significant difference in power Doppler scores for vascularization. We suspected that this finding was a reflection of the high number of dogs undergoing MIPO that were completely healed at the time of the first follow-up examination. Low-power Doppler scores may be due to poor vascularity during healing or normal vascular regression in the last stage of bone healing.

An ultrasonographic study investigating the influence of fracture stability on vessel density and distribution during fracture healing revealed that early vascular response was greater in less rigid bone plate constructs during the first 14 days after surgery. It is likely that the healing pattern observed in dogs that underwent MIPO in the present study depended on both biomechanical and biological factors. An important difference between the treatment groups was the size of the fracture gap. Dogs in the ORIF treatment group underwent anatomic reconstruction of the fracture and had a gap < 1 mm, whereas all dogs in the MIPO treatment group had a fracture gap > 1 mm. Furthermore, in the dogs that underwent MIPO with long plates, fewer screws...
and long plate working lengths were used. The greater plate working length in the MIPO treatment group may be responsible for a less rigid construct than that in the ORIF treatment group, and a less rigid construct would stimulate secondary bone healing. The larger fracture gap in dogs that underwent MIPO would have further contributed to secondary bone healing. The biological advantage of MIPO should also be considered. In a human cadaveric study performed by Borelli et al., percutaneous plating of the tibia caused less disruption of the extraosseous blood supply than did open plating. Periosteal arteries forming the extraosseous blood supply have an important role in the early phase of fracture healing. We hypothesized that MIPO may facilitate bone healing by preserving the soft tissue envelope and the fracture hematoma. In contrast, ORIF may delay the initial phase of healing because of the additional surgical tissue trauma and bone devascularization.

Studies have been conducted to establish whether ultrasonographic examination of fracture sites could provide earlier indication of fracture healing, compared with radiographic examination, in dogs. One of the potential advantages of early detection of fracture healing would be to recognize the development of complications sooner and avoid treatment delays. Additionally, dogs with more rapid healing may return to normal activity levels earlier and have a faster recovery from the initial trauma. The results of the present study suggested that dogs undergoing MIPO would be able to return to function sooner that would dogs undergoing ORIF. Although functional outcomes were not measured in the study dogs, it could be speculated that more rapid healing in the MIPO treatment group would correlate with earlier functional recovery. However, such a study has not yet been performed, to our knowledge. It should also be considered that the difference in healing time between the MIPO and ORIF treatment groups was only 4 weeks, which may not be a clinically relevant difference because the fractures in all dogs healed in < 12 weeks.

In the present study, complete healing determined via ultrasonography was detected earlier than that determined via radiography only in the ORIF treatment group. The results of the present study are in disagreement with those of a previous investigation, which indicated that the difference in healing times assessed via ultrasonography and radiography was more evident in fractures with secondary bone healing. We believe that the first ultrasonographic evaluation performed at 4 weeks after surgery may have been too late to detect complete healing in some dogs that underwent MIPO. Potentially, if follow-up examinations had been scheduled at every 2 weeks, this difference would have been more pronounced because fractures in 2 dogs that underwent MIPO had radiographic signs of union at the first follow-up examination. This finding suggested that dogs undergoing MIPO should be evaluated in the first 2 to 3 weeks after surgery because the fractures may be completely healed and the dogs could return to normal activity < 1 month after surgery. Additionally, on the basis of the results of the present study, radiographic examination appears to be a valid method for detection of early fracture healing following MIPO.

Several limitations should be considered when interpreting the results of the present study. As part of the ultrasonographic evaluation of bone healing, only the number of Doppler signals was used to grade the amount of vascularization at the fracture site, rather than including power Doppler signal intensity and area, because it has been shown that the number of signals alone has similar correlation with the amount of vascularization determined histologically. Furthermore, our choice to evaluate both the amount of vascularization and the localization of the vessels was based on a study describing the vascularization patterns associated with different fixation techniques. That study showed not only that fractures treated with external fixation had more abundant vascularization, but also that the vessels were seen in the surrounding soft tissues and extending into the callus, whereas fractures treated with rigid plate fixation had sparse vascularization located only at the bony surface and not in the surrounding soft tissues. We believed that assessing the localization of neovascularization would also provide an indication of the type of fracture healing (secondary vs direct).

Another limitation was the low number of dogs in the treatment groups. By matching dogs by age, type of fracture, and body weight, we attempted to minimize bias due to confounding variables that would affect the outcome. The low number of dogs may have also affected the statistical results. The lack of significant difference in both ultrasonographic scores between groups may be a type 2 error caused by low statistical power. Future prospective studies should compare outcomes following MIPO and ORIF in a larger group of dogs to elucidate whether MIPO has a clinical advantage over ORIF. Another limitation was that all dogs in the present study were young and of small size; although this enabled the patient profile in each treatment group to be similar, the age and physical stature of the dogs probably influenced the overall results of the study. The advantages of MIPO, compared with ORIF, may be more evident in older dogs because of more protracted healing in older versus younger dogs.

In the present study, ultrasonography and radiography revealed that MIPO is associated with secondary bone healing and faster healing, compared with ORIF, in dogs with simple, closed radius-ulna fractures. Minimally invasive plate osteosynthesis may achieve early bone healing with a balance between preservation of biological processes and appropriate stability of the fixation construct. In dogs that underwent MIPO, the time to complete healing determined via ultrasonography or radiography was similar. Although ultrasonography enables evaluation of early soft callus formation, radiographic evaluation detected bridging callus as early as 2 weeks after surgery. On the basis of the study findings, we suggest that radiographic follow-up examinations should be performed every 2 to 3 weeks for dogs that undergo MIPO for treatment of radius-ulna fractures. In the present study, fractures in all dogs healed eventually in < 3 months. Therefore, further work needs to be done to determine whether MIPO should be recommended over ORIF for treatment of radius-ulna fractures in dogs.
Appendix 1

Stages of fracture healing based on characteristics of B-mode ultrasonographic images used to monitor dogs that underwent MIPO or ORIF for the treatment of coexisting fractures of the radius and ulna.

<table>
<thead>
<tr>
<th>Stage of fracture healing</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tissue within the fracture gap appears anechoic to hypoechoic, with possible hematomas and fragments; no vascularization is visible by use of power Doppler ultrasonography.</td>
</tr>
<tr>
<td>2</td>
<td>Tissue appears hypoechoic (soft tissue callus) but is now heterogeneous; vascularization (determined by use of power Doppler ultrasonography) is clearly present in the soft tissue.</td>
</tr>
<tr>
<td>3</td>
<td>Evidence of bridging of the fracture gap with inhomogeneous tissue (mix of hypoechoic and hyperechoic areas); vascularization (determined by use of power Doppler ultrasonography) is present but less abundant than in stage 2.</td>
</tr>
<tr>
<td>4</td>
<td>Increasingly homogeneous, hyperechoic image of the tissue at the fracture site (acoustic shadow returns); vascularization is still present and appears to be located on the bone surface rather than in the soft tissue.</td>
</tr>
<tr>
<td>5</td>
<td>Mature callus is present; homogeneous, hyperechoic tissue bridging the fracture gap; the surface of this bridge will progressively appear smoother, compared with previous interrogations; vascularization is not detectable by use of power Doppler ultrasonography.</td>
</tr>
</tbody>
</table>

Appendix 2

Radiographic scoring system based on callus formation, appearance of the fracture line, and stage of union used to determine a fracture healing grade as a means to monitor dogs that underwent MIPO or ORIF for the treatment of coexisting fractures of the radius and ulna.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Grade of fracture healing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Callus formation</td>
<td>Homogeneous bone structure</td>
</tr>
<tr>
<td>Fracture line</td>
<td>Omitterated</td>
</tr>
<tr>
<td>Stage of union</td>
<td>Achieved</td>
</tr>
</tbody>
</table>