The radius is the third most frequently fractured bone in dogs, with 85% of radial fractures involving the distal third of the diaphysis. Plate osteosynthesis is one of the most common methods used to stabilize radial fractures in dogs and promotes rapid union as well as rapid return to function. Some studies, however, reveal that up to 54% of small-breed dogs with radial fractures treated with plate osteosynthesis develop complications. In addition, small-breed dogs have a greater risk of developing certain complications, such as delayed union and nonunion, than do large-breed dogs. Although the definitive cause of these complications has yet to be elucidated, biomechanical and vascular characteristics unique to small-breed dogs have been identified as possible risk factors. A microvascular study performed in cadaveric radii revealed that there is decreased microvascular density in the distal diaphyses of small-breed dogs, compared with large-breed dogs, which purportedly might impair bone healing in small-breed dogs. Other biological factors that may contribute to delayed union in small-breed dogs include poor soft tissue coverage of the distal portion of the antebrachium and extensive soft tissue dissection performed during direct fracture reduction. Biomechanical factors such as stiffness and interfragmentary strain of the bone-plate construct may also play a role in the development of complications in small-breed dogs because these variables influence fracture healing. Experimentally, clinically normal dog femurs plated with stiff plates become more osteoporotic than femurs plated with less-stiff plates. Interfragmentary strain is another important mechanical factor because it stimulates the formation of callus and accelerates healing, but excessive motion at the gap may not be tolerated and may be detrimental to callus formation. Radial fractures stabilized with plates in large-breed dogs are associated with an excellent prognosis and rarely develop complications, compared with dogs weighing <...
The purpose of the study reported here was to compare in vitro axial compression, abaxial compression, and torsional stiffnesses of intact and plated radii from small- and large-breed dogs. We hypothesized that plated radii would be stiffer than the intact radii in small-breed and large-breed dogs and that plated radii from small-breed dogs would have a greater relative stiffness than plated radii from large-breed dogs. To test the hypothesis, data were normalized by expressing the stiffness of the plated radii as a percentage of the stiffness of the intact bones and the normalized stiffness of the bone-plate constructs was compared between large- and small-breed dogs.

**Materials and Methods**

**Specimen preparation**—This study was approved by the University of Florida Institutional Animal Care and Use Committee. Eighteen paired antebrachii were harvested from adult male and female dogs that were euthanized for reasons unrelated to this study. Nine of the 18 large-breed dog radii were randomly selected and placed in a group that would be stabilized with a 6-hole 2.0-mm DCP. The remaining large-breed specimens were used in pilot studies. The small-breed dog radii were allocated into 2 stabilization groups. One radius from each pair was randomly assigned to a group that would be stabilized with a 6-hole segment of a 2.0/2.7-mm CTLP.

Prior to testing, both ends of each radius were potted in epoxy resin to the level of the metaphysis by use of a block mold. Two 1.6-mm Kirschner wires were drilled through the resin and each end of the radius at orthogonal angles to further stabilize the potted bone segments. The Kirschner wires were trimmed flush with the surface block. A 3.8-mm drill bit was used to create an indentation in the epoxy block in which the proximal end of the radius was embedded. This indentation was made directly above the radius and was created to ensure that the loading sphere consistently applied force in alignment with the longitudinal axis of the radius throughout testing. A second indentation was made in the proximal epoxy block 8 mm caudal (relative to the radius) to the first indentation for use during abaxial compression testing.

Each radius was then loaded in axial compression, abaxial compression, and torsion by use of a servohydraulic mechanical testing machine to provide control values. An appropriately sized 6-hole plate was contoured and applied to the dorsal surface of each radius, and the screw holes were drilled and tapped. The plate was affixed to the osteotomized radius with 3 cortical screws in each segment, leaving a gap of 1 mm between the 2 radial segments. All screws were placed and hand-tightened by an experienced board-certified surgeon (AP) in accordance with the standard technique. The bone-plate constructs were then tested following the same protocol as for the controls.

**Mechanical testing**—All specimens were tested in axial compression, followed by abaxial compression and then torsion, before and after plating. The order in which the stabilization groups were tested was randomized for each test, as were the order of the specimens within each group. During testing, each specimen was positioned vertically in the mechanical testing machine with the proximal end of the radius facing up and cranial surface of the radius facing the front of the testing machine. The epoxy resin block securing the distal radius was secured into the machine by use of a specially designed fixture (Figure 1). The fixture consisted of 2 metal support rails that could slide along a lower track that was secured to the base of the testing machine. Once adjusted, the rails were locked in place by tightening the bolts that attached the rails to the track.

Two videography cameras were used to evaluate gap motion during testing. One camera recorded images of the entire specimen as the other camera was closely focused on the osteotomy gap. Videographic recording was performed during axial and abaxial compression testing to assess how the specimens deformed and how movement at the osteotomy gap changed during loading.

**Axial compression**—A 25.4-mm diameter stainless steel sphere was secured into the actuator of the testing machine (Figure 1) and used to load the specimens in compression. Each specimen was then placed in the testing machine and positioned such that the sphere engaged the indentation created directly over the radius in the proximal epoxy block. Once aligned, the distal epoxy block was secured into the construct as described. Each specimen was cyclically preloaded 20 times by use of 50% of the test load at a rate of 0.5 Hz. Following preloading, each specimen was axially loaded to twice the mean body weight of the assigned stabilization group; the large-breed dog radii were loaded to 550 N, and the small-breed dog radii were loaded to 100 N. The specimens were loaded.
under load control over 10 seconds, and displacement at 100 Hz was recorded.

**Abaxial compression**—Each radius was again positioned vertically in the testing machine with the loading sphere centered in the caudal notch in the proximal epoxy block. Once aligned, the distal epoxy block was secured into the construct as described. The specimen was then preloaded and tested by use of the same procedure as described for axial compression.

**Torsion**—For the small-breed dog radii, the metal mold that was used for potting the ends of the bones was secured to the actuator of the testing machine by use of C-clamps (Figure 1). The proximal epoxy block was inserted into the mold, and the actuator was lowered until the specimen engaged the lower construct. The distal epoxy block was secured into the construct as described. For the large-breed dog radii, an adjustable fixture, identical to the one affixed to the base of the testing machine, was secured to the load cell by use of C-clamps. Each large-breed dog specimen was placed in the center of the testing machine, and the actuator was lowered until it engaged the proximal epoxy block. The proximal and distal epoxy blocks were then secured into the upper and lower fixtures. Each specimen was cyclically preloaded 20 times by use of 50% of the test load at a rate of 0.5 Hz. Following preloading, each specimen was loaded to 70 N • mm/kg on the basis of the assigned stabilization group’s mean body weight; the large-breed dog radii were loaded to 2,000 N • mm, and the small-breed dog radii were loaded to 350 N • mm. The specimens were loaded under torque control over 10 seconds, and angular displacement at 100 Hz was recorded.

**Measurement of stiffness**—To calculate stiffness, a load-displacement curve was made by plotting the load and displacement data for each specimen during testing in a scattergraph by use of spreadsheet software. A best-fit trend line, straight line slope, and corresponding $R^2$ value were determined with a sum of least squares method for the linear elastic region of the load-displacement curve by use of the same software. The stiffnesses were expressed as absolute values for all intact and plated radii. Normalized stiffness values were also calculated for all plated radii. The normalized stiffness of the plated radii was expressed as a percentage of the stiffness of the intact radii by dividing the stiffness of a plated specimen by the stiffness of that specimen intact and multiplying that quotient by 100.

**Statistical analysis**—Absolute stiffness values were compared between intact and plated radii for all stabilization groups. The main effects of treatment (intact vs plating) and type of plate applied were analyzed by use of a 2 × 3 (intact or plated vs stabilization group) ANOVA with repeated measures and a post hoc Bonferroni test. A separate 2 × 3 ANOVA was performed for each test data set (axial compression, abaxial compression, and torsion test).

The normalized stiffness values of the plated radii were compared among stabilization groups by use of a 1-way ANOVA with a post hoc Bonferroni test. For all statistical analyses, values of $P < 0.05$ were considered significant.

**Results**

The mean ± SD absolute stiffness values of the intact and plated radii were determined (Table 1). The in-
tact large-breed dog radii were significantly stiffer than the intact small-breed radii when loaded in axial compression, abaxial compression, and torsion. The plated large-breed dog radii were significantly stiffer than both groups of plated small-breed dog radii in axial compression, abaxial compression, and torsion. There was no significant difference in intact or plated stiffness between small-breed dog stabilization groups. For all stabilization groups, the intact radii were significantly stiffer than the plated radii when loaded in axial compression and abaxial compression; however, the torsional stiffnesses of the intact and plated bones were not significantly different for any of the treatment groups.

The mean normalized axial compression stiffness values for the large-breed 3.5-mm LCDCP, small-breed 2.0-mm DCP, and small-breed 2.0/2.7-mm CTLP stabilization groups were 74.7 ± 11%, 51.7 ± 12%, and 69.1 ± 12%, respectively. The normalized axial compression stiffnesses of the plated radii in the large-breed dog 3.5-mm LCDCP stabilization group and the small-breed dog 2.0/2.7-mm CTLP stabilization group were significantly greater than the stiffness of the plated radii of the small-breed 2.0-mm DCP group (Figure 2). The normalized stiffnesses of the large-breed dog 3.5-mm LCDCP and the small-breed dog 2.0/2.7-mm CTLP groups were not significantly different.

In abaxial compression, the mean normalized stiffness values for the large-breed 3.5-mm LCDCP, small-breed 2.0-mm DCP, and small-breed 2.0/2.7-CTLP stabilization groups were 85.1 ± 19%, 60.2 ± 25%, and 74.8 ± 11%, respectively. In abaxial compression, the large-breed dog 3.5-mm LCDCP group was significantly stiffer, compared with intact radii, than the small-breed dog 2.0-mm DCP group. The normalized abaxial compression stiffness of the small-breed dog 2.0/2.7-mm CTLP group was not significantly different than the large-breed dog 3.5-mm LCDCP or small-breed dog 2.0-mm DCP stabilization groups (Figure 2). For mean normalized torsion stiffness, the large-breed dog 3.5-mm LCDCP, small-breed dog 2.0-mm DCP, and small-breed dog 2.0/2.7-mm CTLP groups were not significantly different.

Review of the videographic recordings revealed that all plated radii bowed cranially when loaded in compression. The bowing was more pronounced when specimens were loaded in abaxial than in axial compression. During testing, the gap between the caudal cortices of the radial segments closed eccentrically; whereas the cranial cortices did not appreciably change position. This movement reduced the fracture gap; however, the radial segments did not come into contact at any point during testing.

Table 1—Mean ± SD absolute stiffness values for intact and osteotomized and plated radii from large-breed dogs stabilized with a 3.5-mm LCDCP, small-breed dogs stabilized with a 2.0-mm DCP, and small-breed dogs stabilized with a 2.0/2.7-mm CTLP (9 radii/group) and loaded in axial compression, abaxial compression, and torsion.

<table>
<thead>
<tr>
<th>Stabilization group</th>
<th>Radius treatment</th>
<th>Axial compression (N/mm)</th>
<th>Abaxial compression (N/mm)</th>
<th>Torsion (Nm/deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-breed 3.5-mm LC-DCP</td>
<td>Intact</td>
<td>1,472 ± 192a</td>
<td>817 ± 150a</td>
<td>511 ± 74a</td>
</tr>
<tr>
<td></td>
<td>Plated</td>
<td>1,092 ± 153c</td>
<td>686 ± 144c</td>
<td>526 ± 69c</td>
</tr>
<tr>
<td>Small-breed 2.0-mm DCP</td>
<td>Intact</td>
<td>511 ± 63a</td>
<td>254 ± 65a</td>
<td>85 ± 40a</td>
</tr>
<tr>
<td></td>
<td>Plated</td>
<td>268 ± 87b</td>
<td>145 ± 46b</td>
<td>62 ± 20b</td>
</tr>
<tr>
<td>Small-breed 2.0/2.7-mm CTLP</td>
<td>Intact</td>
<td>527 ± 118b</td>
<td>249 ± 20b</td>
<td>76 ± 38b</td>
</tr>
<tr>
<td></td>
<td>Plated</td>
<td>359 ± 67b</td>
<td>187 ± 34b</td>
<td>104 ± 42b</td>
</tr>
</tbody>
</table>

deg = Degree. *Within a column, different superscript letters indicate significant (P < 0.05) differences.

Discussion

Results indicated that all intact radii were significantly stiffer than the plated specimens and that the percentage change in stiffness following plating was not different between small-breed dog radii stabilized with 2.0/2.7-mm CTLPs and large-breed dog radii stabilized with 3.5-mm LCDCPs when loaded in axial compression and abaxial compression. Small-breed dog radii plated with 2.0-mm DCPs were significantly less stiff than radii of any other group, typically with 50% to 60% of the intact bone stiffness. These results suggest that healing complications of plated radial fractures in small-breed dogs may not be caused by excessive rigidity of the stabilized fracture. Considering that the small-breed dog bone-plate constructs had the same or less normalized stiffness than the large-breed dog constructs, it is unlikely that excessive stiffness of the bone-plate construct is responsible for the bone resorption and high complication rate observed in small-breed dogs with radial fractures. 

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Fixation stiffness affects the pattern of healing in long bone fractures. Rigid fixation is a prerequisite for primary bone healing. Flexible fixation typically stimulates abundant external callus formation, which may result in more rapid union. In a study that used intramedullary rods of varied stiffnesses in osteotomized rabbit femurs, Wang et al found that an implant-construct stiffness of 20% to 50% of the stiffness of the intact bone resulted in a union with the greatest strength (load at failure) throughout all phases of healing. In an experimental study performed in dogs, Foux et al found that osteotomized femora stabilized with an axially flexible plating system healed faster and reached greater flexural rigidity than did osteotomized femora stabilized with DCP. Terjesen and Apalset evaluated the 4-point bending stiffness of healed tibial osteotomies in rabbits following fixation with plates of stiffness ranging from 13% to 74% of the stiffness of the intact tibiae. They concluded that greater stiffness and strength (load to failure) of the healing bones occurred in groups plated with less rigid implants, ranging from 20% to 60% of the intact tibiae. In the present study, when only small-breed dog groups were compared, 2.0-mm DCP bone-plate constructs were significantly less stiff than 2.0/2.7-mm CTLP bone-plate constructs. This result can be explained by the lower implant stiffness of 2.0-mm DCPs, compared with the 2.0/2.7-mm CTLP. Clinical guidelines cannot be established on the basis of results of an in vitro study; however, only the 2.0-mm DCP constructs had stiffness within the reported 20% to 60% optimal range. These results suggest that the 2.0-mm DCP or a plate with a lower stiffness relative to the intact radius might be preferable for stimulating callus production and strength in small-breed dogs.

Shear stress at the fracture site may be detrimental to optimal fracture healing, leading to longer healing times and weaker callus formation. Therefore, an optimal fixation implant should be stiff enough in torsion to minimize shear motion. All plated constructs evaluated in the present study reestablished the original torsional stiffness of the bone. This finding suggested that all plates evaluated in the present study were appropriate to neutralize shear motion at the fracture site caused by torsional forces.

Our testing methodology was designed to mimic in vivo physiologic loading as closely as possible. Studies have suggested that the radii of a trotting dog are often subject to axial forces of 100% to 200% of body weight. On the basis of these observations, radii were loaded to 200% of mean body weight during axial and abaxial compression testing. The torsional forces applied were selected on the basis of those used in a previous study and were interpreted on a per weight basis for use in the present study. We chose to test the specimens in both axial and abaxial compression because radii are subjected to axial and abaxial compressive forces during ambulation. Abaxial compressive forces originate caudally on the radius, creating torsional stress in the cranial cortex and compression in the caudal cortex. To test the radii in abaxial compression, we attempted to recreate these forces by eccentrically loading the bones 8 mm caudal to their central longitudinal axis. This value was the mean cranio-caudal mid-diaphyseal width of all specimens, in the cranio-caudal direction. Because all applied loads were calculated on a per weight basis, choosing 8 mm as the caudal offset for all specimens kept a consistent bending moment among groups.

In the present study, the authors selected a 1-mm gap to create a repeatable model with minimal variability between specimens. Small fracture gaps are often present in clinical cases when there is mild comminution or poor interfragmentary compression of the fracture. Gap width may vary in dogs of different sizes in vivo because of the influence of the different sizes of plates and screws. In the present study, the gap corresponded to the thickness of the blade used to osteotomize the bone before plate application and was constant among all specimens. The effect of gap stiffness of bone-plate constructs was recently evaluated by use of mechanical testing and finite element analysis. The mechanical experiment revealed a 2-phase stiffness pattern in all specimens. The initial stiffness represented the stiffness of the construct before the fracture ends contacted. The second stiffness was the stiffness that occurred after there was contact between the ends of the fracture segments. The load-displacement curves that were analyzed in the present study revealed plotted data with a single slope, suggesting a single-phase stiffness pattern. This result was consistent with the observation that the ends of the fracture segments did not come into contact during testing, which would have resulted in a second stiffness phase.

Bone resorption under the plate is reported more often in small-breed dogs than in large-breed dogs. Weakened bone resulting from resorption may be caused by 2 processes: the plate and screws interfering with cortical blood supply causing necrosis followed by porosis or rigid plates causing stress shielding followed by structural changes according to Wolff’s law. Although the present study did not examine stress shielding specifically, it measured the stiffness of the bone-plate construct, which is one of the factors contributing to stress shielding. Because the normalized stiffnesses of the 2 small-breed dog bone-plate constructs were not different or significantly less than the values of the 3.5-mm LCDCP group, it is unlikely that the stiffness of the plates used in small-breed dogs is the main factor causing bone resorption. A vascular mechanism for adaptation osteopenia as reported by Field and Sumner-Smith may be a more likely cause for the osteopenia seen in small-breed dogs.

One limitation of this study was that it did not mimic the loading rate that the radius would experience in vivo. During ambulation, the bone is loaded and unloaded in <0.25 seconds; however, we chose a quasistatic loading rate to minimize any effect the radius’ viscoelastic properties might contribute that could obscure the observed stiffness. The values were reported as percentages of intact bone before plating to compare stiffnesses among radii of different sizes; however, geometric and material properties may be more appropriate factors for normalization than stiffness. The importance of this variation is unknown, but geometric factors substantially affect the mechanical properties of bone. Because of these morphological differences, different plates may have been used in vivo for certain bones than the plates applied in this study. Another limitation is that, although this study attempted to close-
ly mimic physiologic conditions, it is possible that these specimens would respond differently in vivo; however, we are unable to predict how our results would compare with results of an in vivo study. Also, most fractures in small-breed dogs occur in the diastal diaphysis or metaphysis. We chose to perform mid-diaphyseal osteotomies because of the need to pot the ends of the bones and the difficulty of standardizing distal osteotomies.

On the basis of results of this study, it is unlikely that complications associated with the healing of plated radial fractures in small-breed dogs can be ascribed to an excessively stiff bone-plate construct. Although internal bone stresses were not evaluated, the similar normalized stiffnesses of the small- and large-breed plated radii suggest that biological factors, rather than biomechanical factors, are more likely responsible for the healing complications reported in small-breed dogs.

a. Synthes USA, Paoli, Pa.
b. Bondo Corp. Atlanta, Ga.
c. MTS 889 Mini Bionix II, MTS Systems Corp, Eden Prairie, Minn.
d. Mini driver K100 with K148 blade (0.6 mm), 3M, Maplewood, Minn.
e. Microsoft Office Excel 2003, Microsoft Corp, Redmond, Wash.

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