Cortical Bone Graft and Endoprosthesis in the Distal Radius of Dogs: A Biomechanical Comparison of Two Different Limb-Sparing Techniques

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Objective—To compare the biomechanical properties of cortical bone and surgical steel endoprosthesis for limb-sparing surgery of the distal radius in dogs and evaluate the role of the ulna in providing stability to the reconstructed limb.

Study Design—Cadaveric biomechanical study.

Animals—Twelve pairs of normal canine thoracic limbs.

Methods—Paired limbs were divided into 4 groups: endoprosthesis and cortical bone graft, with and without preservation of the ulna. In each limb pair, the distal segment of the radius resected from the limb to be reconstructed with an endoprosthesis was used as the cortical bone graft in the contralateral limb. The ulna was resected en bloc with the radius and at the same level as the radial osteotomy in limbs where the ulna was not preserved. Limbs were tested in axial loading until failure. The load–deformation curve was used to acquire the biomechanical properties of each construct, which were compared using 2-way ANOVA. Failure modes were compared descriptively.

Results—Limbs reconstructed with the endoprosthesis had significantly greater yield load, energy at yield, and ultimate load compared with limbs reconstructed with a cortical bone graft. There were no significant differences in either energy to failure or stiffness between the 2 constructs. Preservation of the ulna did not significantly improve any of the biomechanical properties tested with either endoprosthesis or cortical bone graft constructs. The modes of failure in all 4 groups were variable and inconsistent.

Conclusions—Limbs reconstructed with an endoprosthesis were biomechanically superior to limbs reconstructed with a cortical bone graft in axial loading to failure. Preservation of the ulna is not required to improve the stability in axial compression after limb-sparing surgery of the distal radius.

Clinical Relevance—The endoprosthesis may provide another option for limb-sparing surgery of the distal radius in dogs. It has potential advantages when compared with cortical bone grafts, including better biomechanical performance and resistance to implant failure in axial compression, immediate availability, and no requirement for bone banking facilities. The ulna can be resected en bloc with the radius without having a negative impact on construct stability. En bloc resection of the ulna and radius may decrease the risk of local tumor recurrence after limb-sparing surgery.
INTRODUCTION

OSTEOSARCOMA (OSA) is the most common primary bone tumor of the canine skeleton.1 In dogs, OSA has a predilection for the metaphyseal region of the appendicular skeleton of middle-aged, large breed dogs and the distal radius is the most commonly affected site.1 The gold standard curative-intent treatment for dogs with appendicular OSA involves limb amputation for control of the local tumor and adjuvant chemotherapy for management of metastatic disease.1,2 Limb-sparing surgical techniques have become the standard of care in humans with primary bone tumors and are a viable alternative to limb amputation in dogs, especially if concomitant conditions exist which are relative or absolute contraindications for limb amputation, such as neurologic disease or debilitating osteoarthritis, or if owners are reluctant to proceed with limb amputation.1,2 Limb-sparing surgery involves tumor resection and reconstruction of the bony column, with or without arthrodesis of the adjacent joint.1,2 Limb-sparing procedures have been described for the distal aspect of the radius, proximal aspect of the humerus, distal aspect of the tibia, and proximal aspect of the femur in dogs with OSA, but limb-sparing surgery for tumors of the distal aspect of the radius has produced the most favorable results.3–12 This is largely because pan-carpal arthrodesis is well tolerated in dogs, whereas arthrodesis of other sites (e.g. shoulder, stifle, and tarsus) is associated with poor postoperative limb function.3,9,13–15

Cortical allografts have traditionally been used to reconstruct the radius after tumor resection.3–4 Use of massive allografts is associated with a high complication rate in both human and veterinary patients, including infection, fracture, implant failure, and tumor recurrence.3–4 As a result, surgeons have been investigating alternative methods of reconstructing the bone defect in an attempt to decrease the complication rate, especially infection and implant failure. These methods include distraction osteogenesis using circular fixators,5,6,10 and vascularized,7 irradiated,11 and pasteurized autografts.8 Most techniques are limited by surgical training and expertise (e.g. distraction osteogenesis and vascularized autografts), access to specialized equipment and facilities (e.g. vascularized and irradiated autografts), and surgeon experience.

Recently, a 316L surgical steel endoprosthesis prototype has become commercially available for canine limb-sparing surgery (Veterinary Orthopedic Implants, Burlington, VT). This first-generation endoprosthesis consists of a solid 122 mm segment of surgical steel with a flared distal end to abut the radial carpal bone and 2 machined screw holes at the distal and proximal ends to secure the dedicated limb-sparing plate. The 24-hole limb-sparing plate has a greater cross-sectional area than either a 3.5 mm broad or 4.5 mm narrow dynamic compression plates (DCP), round rather than oval screw holes to increase the amount of surgical steel per unit length of plate, screw hole diameters for the proximal aspect of the radius and radial carpal bone which accommodate 3.5 and 4.5 mm cortical bone screws and 4.0 mm cancellous bone screws, and a tapered distal end for the metacarpus with screw holes accommodating either 2.7 or 3.5 mm cortical bone screws. The potential advantages of an endoprosthesis for the reconstruction of bone defects in limb-sparing surgery include a readily available implant with no need for special equipment, bone banking facilities or external beam radiation therapy machines. Furthermore, the implantation of a biologically inert material may decrease the incidence and severity of postoperative infection commonly encountered in cortical allograft limb-sparing surgery by avoiding allogeneically induced foreign body reactions.16 However, the biomechanical properties of limbs reconstructed with this first-generation surgical steel endoprosthesis are unknown and the difference in structural properties between bone and solid steel may increase the risk of implant complications and failure.

Our purposes were to compare the biomechanical properties of the canine radius reconstructed with either a cortical bone graft or first-generation surgical steel endoprosthesis and to evaluate the role of the ulna in providing stability to the reconstructed radius. We hypothesized that an endoprosthesis-reconstructed limb would be stronger and stiffer than a cortical bone graft-reconstructed limb under axial loading and the difference in the modulus of elasticity between these 2 implants would result in a different mode and higher rate of implant failure in limbs reconstructed with the endoprosthesis. We also hypothesized that the intact ulna would not improve the biomechanical performance of cadaveric limbs reconstructed with either cortical bone grafts or endoprostheses.

MATERIALS AND METHODS

Limb Collection and Preparation

Paired thoracic limbs were harvested from 12 skeletally mature dogs euthanatized for reasons unrelated to this study. Thoracic limbs were used if the dog's body weight was > 30 kg, radius length was > 25 cm, and there was no historical or gross evidence of skeletal disease. Paired thoracic limbs were harvested with skin and musculature intact and sealed in a single plastic bag to prevent dessication, labeled, and frozen at −80°C within 24 hours of euthanasia.

Surgical Technique

Lims were thawed at room temperature for 19–24 hours before resection of the distal aspect of the radius and recon-
struction. An endoprosthesis and cortical bone graft were used to reconstruct each pair of limbs and paired limbs were randomly assigned to have their ulna either preserved or resected. Hence, thoracic limbs were assigned to 1 of 4 groups of 6 limbs each: (1) distal aspect of the radius reconstructed with a cortical bone graft and preservation of the ulna; (2) distal aspect of the radius reconstructed with a cortical bone graft and resection of the ulna; (3) distal aspect of the radius reconstructed with an endoprosthesis and preservation of the ulna; and (4) distal aspect of the radius reconstructed with an endoprosthesis and resection of the ulna.

A 110 mm segment of the distal aspect of the radius was resected using a standard limb-salvage technique. Briefly, a dorsal approach to the radius and carpus was performed, the distal 80% of the radius was isolated by blunt and sharp dissection, and the radius was osteotomized 110 mm proximal to the antebrachiocarpal joint with an oscillating saw. The ulna was either resected at the level of the radial osteotomy or preserved, depending on the experimental group assignment. The distal antebrachial segment was then removed after disarticulation at the antebrachiocarpal joint, if both the radius and ulna were resected, and the distal aspect of the radioulnar joint, if the ulna was preserved. The proximal aspect of the radial and ulnar carpal bones was removed with an oscillating saw to provide a flat surface to abut the distal end of the endoprosthesis or cortical bone graft.

The osseous defect was filled with either a cortical bone graft or endoprosthesis (Fig 1A–C). The distal segment of radius resected from the limb to be reconstructed with an endoprosthesis was used as the cortical bone graft in the paired contralateral limb. The distal articular surface of the radial segment was osteotomized and the medullary canal opened by drilling from the osteotomized surface into the medullary canal. The cortical bone graft was filled with polymethylmethacrylate (PMMA; Surgical Simplex P, Stryker Howmedica Osteonics, Rutherford, NJ) in accordance with current limb preservation recommendations. The cortical bone graft and endoprosthesis was secured to the limb with a limb-sparing plate (Veterinary Orthopedic Implants), including four 3.5 mm cortical bone screws in the proximal radius, two 3.5 mm cortical bone screws (in the cortical bone graft) or specialized screws (in the endoprosthesis), and seven 3.5 cortical bone screws in the radial carpal bone and third metacarpal bone (Fig 2). A minimum of 50% of the length of the metacarpal bone was covered by the plate. The limb-sparing plate was applied without prebending using standard AO/ASIF technique. Limb reconstruction was performed by a single surgeon (J.M.L). After reconstruction, the limbs were frozen at –80°C until biomechanical testing.

**Biomechanical Testing**

Constructs were thawed at room temperature for 24 hours before biomechanical testing. The humerus was osteotomized approximately 5 cm distal to the humeral head. The distal end of the humerus was potted in a custom-designed aluminum fixture using high-strength potting compound (Dynacast, Kindt Collins, Cleveland, OH) to the level of the distal humeral epiphysis. Ligamentous structures of the elbow were preserved but the remaining soft tissues were removed. The potted humerus was attached to the actuator of a materials testing machine (MTS, Eden Prairie, MN) using a custom fixture (Fig 3). The paw was positioned directly over the load cell to yield an elbow flexion angle of ~125° and a reconstruction offset from the vertical of 10°. To prevent slippage during axial loading, the paw was potted in high-strength dental plaster (Resinrock Die Material, Whip Mix, Louisville, KY).

Four limb constructs, 1 from each group, were initially cycled from 30% to 100% of body weight to simulate a clinical setting, but there was no evidence of failure in any of the 4 tested limbs after 100,000 cycles. As a result, we decided to discontinue this mode of biomechanical testing and tested the remaining limbs in axial loading to failure.

All limbs were preconditioned to eliminate artifacts associated with settling of the fixture and specimen by applying a dynamic loading regimen consisting of cyclic compressive
loads ranging from 30% to 100% of body weight for 30 cycles at 2 Hz. After preconditioning, the constructs were ramped to failure in axial compression at a rate of 300 N/s. Failure mode was documented for each limb. During axial loading, force (N) and displacement (mm) data were acquired at 100 Hz. The following mechanical response variables were derived from the resulting force–displacement curve: construct stiffness (N/mm), yield load (N), ultimate load (N), yield energy absorbed (N mm), and ultimate energy absorbed (N mm). Stiffness was calculated from the linear region of the force–displacement curve using a least squares regression. The yield point was defined as the point where deviation from the calculated stiffness decreased by 20%. Ultimate load was taken as the maximum force registered during testing. Yield and ultimate energies were calculated by integrating regression curves fitted to each force–displacement curve using Mathcad 2000 (Mathsoft Engineering & Education, Cambridge, MA) and incorporating the appropriate upper and lower displacement limits.

**Statistical Analysis**

A 2-way ANOVA was used to determine differences in the response variables with respect to implant (cortical bone graft versus endoprosthesis), ulna (preservation or resection), and percentage of radius replaced by either the endoprosthesis or cortical bone graft. A paired t-test was used to assess the influence of percentage of radius replaced between treatment groups. A simple correlation analysis was used to evaluate the role of resection or preservation of the ulna on the mode of failure. The significance level for all statistical analyses was set at $P \leq .05$. A power of 85% was calculated during the study design using peak load at failure and variability of biomechanical testing from a similar study.21

### RESULTS

**Endoprosthesis and Cortical Graft Comparison**

- **Ulna Preserved.** Endoprosthesis-reconstructed limbs had significantly greater load at yield ($P = .0148$; Fig 4), energy at yield ($P = .0143$), and ultimate load ($P = .0063$, Fig 5) compared with cortical bone graft-reconstructed limbs (Table 1). Limbs reconstructed with an endoprosthesis had 47% greater yield load, 64% greater yield energy, and 41% greater ultimate load than limbs reconstructed with cortical bone grafts. There was no significant difference between the 2 constructs in energy at failure ($P = .6915$) and stiffness ($P = .1856$; Fig 6).

- **Ulna Resected.** Endoprosthesis-reconstructed limbs had significantly greater load at yield ($P = .0025$), energy at yield ($P = .0018$), and ultimate load ($P = .0022$) compared with cortical bone graft-reconstructed limbs (Fig 7, Table 2). Limbs reconstructed with an endoprosthesis had 85% greater yield load, 133% greater yield energy, and 61% greater ultimate load than limbs reconstructed with cortical bone grafts. There was no significant difference between the 2 constructs in energy at failure ($P = .9479$; power = 0.15) and stiffness ($P = .1131$; power = 0.40).

Mean radial length replaced by cortical bone graft was 7 mm less than the endoprosthesis because of removal of the articular surface of the radius to provide a flat surface to abut the radial carpal bone. For limbs where the ulna...
was resected, the mean percentage of radius resected was not significantly different \((P = .41)\) between the cortical bone graft (62.2%) and endoprosthesis (63.5%) groups.

For limbs where the ulna was preserved, the mean percentage of radius resected was also not significantly different \((P = .36)\) between the cortical bone graft (58.9%) and endoprosthesis (60.2%) groups. However, regardless of group assignment, longer radii (or smaller percentage of radius replaced by either the cortical bone graft or endoprosthesis) had strong correlations to greater load at yield \((P = .006)\) and ultimate load \((P = .03)\) and approached significance for energy at yield \((P = .0513)\).

**Ulna Preservation or Resection**

Preservation of the ulna did not significantly improve any of the biomechanical variables tested in limbs reconstructed with either an endoprosthesis or cortical bone graft (Table 4). There was no significant association between preservation and resection of the ulna and either construct failure or mode of failure.

**Modes of Failure**

Failure occurred in the region of the construct \((n = 16)\) or unrelated to the construct (e.g., fracture of the humerus \([n = 7]\) or elbow luxation \([n = 1]\)). Five limbs \((41.7\%)\) reconstructed with an endoprosthesis failed at either the metacarpus \((n = 4)\) or proximal radius \((n = 1;\) Table 5). In 2 of these constructs, dorsal bending of the bone plate occurred in association with bony failure. Construct failure was observed in 2 limbs \((33.3\%)\) with the ulna resected and 3 limbs \((50.0\%)\) with the ulna preserved. In the remaining 7 limbs \((58.3\%)\), the metacarpus–endoprosthesis–radius construct remained intact and failure was caused by fracture of the humerus at the junction of the potting mix and humerus. There were no significant differences in the biomechanical performance of endoprosthesis-reconstructed radii failing within the region of the construct and at the humerus, and hence all limbs were included for statistical analyses.

Eleven limbs \((91.7\%)\) reconstructed with a cortical bone graft failed at the metacarpus, distal or proximal cortical bone graft–host bone interface, cortical bone graft, or proximal radius (Table 5). In 7 of these constructs, dorsal bending of the bone plate occurred in association with failure of either the host bone or cortical bone graft (Fig 8). Construct failure was observed in 5 limbs \((83.3\%)\) with the ulna resected and all limbs \((100\%)\) with the ulna preserved. The remaining limb failed because of elbow luxation.

**DISCUSSION**

Limb-sparing surgery in dogs often involves arthrodesis of the adjacent joint because of the metaphyseal location of primary bone tumors and lack of prosthetic joint replacement techniques for the most frequently reported tumor sites (e.g., carpus, shoulder, hock, and stifle).\(^1,2\) Limb-sparing surgery is most commonly performed for primary bone tumors of the distal radius because pancarpal arthrodesis is well tolerated in dogs,\(^3,4,13–15\) whereas arthrodesis of other joints is often associated with poor postoperative limb function and a high implant-failure rate.\(^1,2,9\) A number of limb-sparing surgical procedures have been described for the distal aspect of the canine radius.\(^3–8\) Massive cortical allografts have traditionally been used for limb-sparing surgery in both dogs and humans. However, because of high complication rates with cortical allografts, alternative techniques are being investigated in the hope they may

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**Table 1. Effect of Limb-Sparing Reconstruction Technique with Preservation of the Ulna**

<table>
<thead>
<tr>
<th>Reconstruction</th>
<th>Stiffness (N/mm)</th>
<th>P-Value</th>
<th>Load (N)</th>
<th>P-Value</th>
<th>Energy (N mm)</th>
<th>P-Value</th>
<th>Load (N)</th>
<th>P-Value</th>
<th>Energy (N mm)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endoprosthesis</td>
<td>245 ± 33</td>
<td>.1856</td>
<td>3260 ± 603</td>
<td>.0148</td>
<td>22088 ± 6064</td>
<td>.0143</td>
<td>3445 ± 418</td>
<td>.0063</td>
<td>31043 ± 1536</td>
<td>.6915</td>
</tr>
<tr>
<td>Cortical graft</td>
<td>195 ± 48</td>
<td></td>
<td>2225 ± 913</td>
<td></td>
<td>13472 ± 6415</td>
<td></td>
<td>2446 ± 784</td>
<td></td>
<td>27918 ± 9967</td>
<td></td>
</tr>
</tbody>
</table>

Mean (± SD) mechanical properties of canine limbs after limb-sparing reconstruction with cortical graft or endoprosthesis.
decrease the risk of complications, particularly infection. These techniques include vascularized autografts and intercalary bone transport with circular external fixators.5–7 Endoprostheses are commonly used in humans for limb-sparing surgery, especially for joint preservation22–29 and expandable endoprostheses in children so that the growth rate of the spared limb can be matched to the contralateral limb.30–36 However, the use of an endoprosthesis for limb-sparing surgery of the distal aspect of the radius in dogs has not been investigated biomechanically or clinically.

We compared the biomechanical characteristics of a commercially available first-generation surgical steel endoprosthesis with a cortical bone graft. The cortical bone graft consisted of the distal radial segment of the contralateral paired limb and hence was an autograft rather than an allograft. However, the cortical radial autograft was treated like an allograft (e.g. storage at –80°C and slow thaw) and would be expected to have similar biomechanical properties to a massive cortical allograft.37,38 In axial loading, limbs reconstructed with an endoprosthesis were significantly stronger, both at the yield and failure points, compared with cortical bone grafts. Endoprosthesis constructs also absorbed significantly greater amounts of energy during both the elastic and elastic–plastic phases of the load–deformation curve before yield and failure, respectively. However, there were no significant differences in stiffness between limbs constructed with either an endoprosthesis or cortical bone graft, despite the endoprosthesis constructs being 26–33% stiffer than cortical bone constructs (slope of the elastic phase), there was no significant difference in stiffness between the 2 constructs.

We hypothesized that limbs reconstructed with an endoprosthesis would be stronger and stiffer than limbs reconstructed with cortical bone grafts. Furthermore, we postulated that endoprosthesis constructs would be more prone to orthopedic failure based on our clinical experience and supposition that differences in the modulus of elasticity between the endoprosthesis and cortical bone would result in stress concentration at the endoprosthesis–host bone interfaces and abnormal load transfer to the proximal radius. In client-owned dogs, we have observed screw and plate loosening in the proximal aspect of the radius in ∼30% of dogs undergoing limb-sparing surgery with an endoprosthesis (unpublished data). However, despite these clinical observations, the latter part of our hypothesis proved incorrect. The most likely explanation for this finding was the lack of significant differences in stiffness between the 2 constructs. Stiffness is the ability of a material to resist being deformed when a force

Table 2. Effect of Limb-Sparing Reconstruction Technique with Resection of the Ulna

<table>
<thead>
<tr>
<th>Reconstruction</th>
<th>Stiffness (N/mm)</th>
<th>P-Value</th>
<th>Load (N)</th>
<th>P-Value</th>
<th>Energy (N mm)</th>
<th>P-Value</th>
<th>Load (N)</th>
<th>P-Value</th>
<th>Energy (N mm)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endoprosthesis</td>
<td>247 ± 85</td>
<td>.1131</td>
<td>2922 ± 563</td>
<td>.0025</td>
<td>20327 ± 4893</td>
<td>.0018</td>
<td>3053 ± 528</td>
<td>.0022</td>
<td>25269 ± 8080</td>
<td>.9479</td>
</tr>
<tr>
<td>Cortical graft</td>
<td>186 ± 74</td>
<td></td>
<td>1580 ± 543</td>
<td></td>
<td>8743 ± 4686</td>
<td></td>
<td>1901 ± 466</td>
<td></td>
<td>25873 ± 17952</td>
<td></td>
</tr>
</tbody>
</table>

Mean (± SD) mechanical properties of canine limbs after limb-sparing reconstruction with cortical graft or endoprosthesis.
6.35 N/kg.40,41 Peak vertical forces increase to 120% of body weight at the walk with a peak vertical force of 94 cm.43 The median body weight of dogs in our study was 31.8 kg, resulting in a peak vertical force of approximately 200 N at the walk, 400 N at the trot, and 1336 N after jumping. The mean yield load for cortical bone graft (1580–2225 N) and endoprosthesis (2922–3260 N) constructs exceeded the peak vertical ground reaction force at a trot by up to 5- and 8-fold, respectively. Furthermore, the mean yield loads for both constructs were greater than the expected peak vertical force after a jump from a moderate height. Only 2 constructs, both cortical bone grafts with resection of the ulna, yielded at loads <1336 N. Yield data are important clinically as these are the loads that can be sustained without resulting in permanent deformation of the material being tested.39,42 Hence, the loads reported for normal to moderate activity are within the elastic phase for all limbs reconstructed with an endoprosthesis and the majority reconstructed with a cortical bone graft. Catastrophic failure occurred at loads 142–183% and 229–258% greater than the jumping load in limbs reconstructed with cortical bone grafts and endoprostheses, respectively. Based on these data, cortical bone grafts and endoprostheses are suitable materials for limb-sparing surgery in dogs as both constructs should be able to tolerate normal postoperative activity in large breed dogs.

A single axial load was applied to the constructs in this study and the effects of cyclic loading were not critically evaluated. Cyclic loading may increase the risk of implant loosening and failure over time because of the effects of repetitive submaximal trauma.39 The effects of cyclic loading on implant stability may also account for our clinical observations. In a preliminary study, 4 limbs reconstructed with either cortical bone grafts or endoprostheses did not fail after 100,000 cycles at 30–100% of body weight. The number of strides (or cycles) for a dog during recovery has been estimated at 4500 cycles/h at a walk and 9000 cycles/h at a trot.44 Therefore, with 1 hour of activity/day, 100,000 cycles represents approximately 22 days of walking and 11 days of trotting. Implant failure in dogs treated with limb-sparing surgery is usually a long-term complication with most implant failures reported >6 months postoperatively.3,4,18 The 4 tested limbs did not fail because 100,000 cycles probably is not representative of the cyclic loading required to result in implant failure. One million cycles would more accurately simulate the clinical situation, but this would be time consuming and possibly cost prohibitive.

**Failure Modes**

Construct failure was observed in 42% of limbs reconstructed with an endoprosthesis and 92% of limbs reconstructed with a cortical bone graft. Modes of failure

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Table 3. Effect of Ulna Preservation or Resection after Limb-Sparing Reconstruction with Endoprostheses

<table>
<thead>
<tr>
<th>Reconstruction</th>
<th>Stiffness (N/mm)</th>
<th>P-Value</th>
<th>Load (N)</th>
<th>P-Value</th>
<th>Energy (N mm)</th>
<th>P-Value</th>
<th>Load (N)</th>
<th>P-Value</th>
<th>Energy (N mm)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ulna Preserved</td>
<td>245 ± 33</td>
<td>.9548</td>
<td>3260 ± 603</td>
<td>.5893</td>
<td>22088 ± 6064</td>
<td>.2452</td>
<td>3445 ± 418</td>
<td>.1856</td>
<td>31043 ± 1536</td>
<td>.4656</td>
</tr>
<tr>
<td>Ulna resected</td>
<td>247 ± 85</td>
<td></td>
<td>2922 ± 563</td>
<td></td>
<td>20327 ± 4893</td>
<td></td>
<td>3053 ± 528</td>
<td></td>
<td>25269 ± 8080</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Effect of Ulna Preservation or Resection after Limb-Sparing Reconstruction with Cortical Grafts

<table>
<thead>
<tr>
<th>Reconstruction</th>
<th>Stiffness (N/mm)</th>
<th>P-Value</th>
<th>Load (N)</th>
<th>P-Value</th>
<th>Energy (N mm)</th>
<th>P-Value</th>
<th>Load (N)</th>
<th>P-Value</th>
<th>Energy (N mm)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ulna Preserved</td>
<td>195 ± 48</td>
<td>.8215</td>
<td>2225 ± 913</td>
<td>.1124</td>
<td>13472 ± 6415</td>
<td>.1563</td>
<td>2446 ± 784</td>
<td>.1115</td>
<td>27918 ± 9967</td>
<td>.7861</td>
</tr>
<tr>
<td>Ulna resected</td>
<td>186 ± 74</td>
<td></td>
<td>1580 ± 543</td>
<td></td>
<td>8743 ± 4686</td>
<td></td>
<td>1901 ± 466</td>
<td></td>
<td>25873 ± 17952</td>
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</tr>
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</table>
for both constructs were variable and inconsistent. In a previous study investigating the biomechanical characteristics in axial loading to failure of an ulnar transposition graft and cortical bone graft for limb-sparing surgery, 50% of limbs reconstructed with a cortical bone graft failed because of caudal bending of the plate and the remaining 50% failed because of metacarpal fracture.21 In our study, only 1 limb (8%) reconstructed with a cortical bone graft failed because of metacarpal fracture. Four limbs (33%) reconstructed with an endoprosthesis failed at the metacarpus, but only 1 of these limbs failed because of metacarpal fracture at the end of the plate with the remaining limbs failing because of fracture through a screw hole or screw pullout. The recommended coverage of the metacarpal bone for pancarpal arthrodesis to minimize the risk of metacarpal fracture at the end of the bone plate varies from >50% for non-tumor arthrodesis to ≥80% for limb-sparing allograft-arthrodesis.19,21 A minimum of 50% of the metacarpus was covered by the bone plate in our study.

Metacarpal fracture without plate deformation was the cause of construct failure in 50% of limbs reconstructed with a cortical bone graft and 3.5 mm broad DCP21 and 100% of limbs in which pancarpal arthrodesis was performed with a 3.5 mm DCP.45 The major differences between these and our study was the type of bone plate used and bone plate application. We used a dedicated limb-sparing plate, rather than a 3.5 mm broad DCP, which is similar to a hybrid pancarpal arthrodesis DCP as the distal aspect of the plate is tapered in both width and depth and can accommodate 2.7 mm cortical bone screws.15 The tapered portion of the limb-sparing bone plate, with a smaller cross-sectional diameter than the remainder of the bone plate, may transfer more of the weight bearing load to the metacarpus and decrease stress concentration at the end of the bone plate in comparison with a 3.5 mm broad DCP. If true, this greater load sharing may decrease the risk of metacarpal fracture at the end of the bone plate.

Plastic deformation of the bone plate was observed in 2 limbs reconstructed with an endoprosthesis (16.7%) and 7 limbs reconstructed with a cortical bone graft (58.3%). In both cases where plate bending occurred in endoprosthesis constructs, plate failure was associated with metacarpal fracture or screw pullout from the metacarpus. For limbs reconstructed with a cortical bone graft, plate bending was associated with distal ulnar fracture in 3 limbs, fracture through a cortical bone graft screw hole in 2 limbs, fracture through a proximal radius screw hole in 1 limb, and at the proximal graft–host bone interface in 1 limb. In all of these cases, failure occurred because of dorsal bending of the bone plate. In contrast, plate deformation in the cortical bone graft group of the aforementioned limb-sparing biomechanical study uniformly occurred at the distal graft–radial carpal bone interface with caudal bending of the bone plate.21

### Table 5. Modes of Failure of Limbs Reconstructed with Endoprostheses and Cortical Bone Grafts

<table>
<thead>
<tr>
<th>Failure Method</th>
<th># Failed</th>
<th># with Plate Bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metacarpal fracture at plate end</td>
<td>1/0</td>
<td>1/0</td>
</tr>
<tr>
<td>Metacarpal fracture at screw hole</td>
<td>2/1</td>
<td>0</td>
</tr>
<tr>
<td>Metacarpal bone plate pullout</td>
<td>1/1</td>
<td>0</td>
</tr>
<tr>
<td>Distal graft/prosthesis-host interface</td>
<td>0</td>
<td>4/4</td>
</tr>
<tr>
<td>Graft/prosthesis fracture at screw hole</td>
<td>0</td>
<td>2/2</td>
</tr>
<tr>
<td>Proximal graft/prosthesis-host interface</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Proximal radius fracture at screw hole</td>
<td>1/0</td>
<td>4/1</td>
</tr>
<tr>
<td>Proximal radius bone plate pullout</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>5/2</td>
<td>11/7</td>
</tr>
</tbody>
</table>

Fig 8. Failure of a cortical bone graft construct after axial loading with fracture through the distal screw hole of the bone graft and dorsal bending of the plate (arrow).

**Role of Prebending of the Plate**

The recommended angle for bending the bone plate at the antebrachiocarpal joint for pancarpal arthrodesis in dogs varies from 10 to 15° in extension.46,47 In our study, the bone plate was applied without prebending (i.e. 0°) while the bone plate was prebent to 10° extension in the previous limb-sparing biomechanical study.21 In both studies, axial load was applied at the same rate until failure. Despite using the identical biomechanical test and similar constructs, the bone plate failed because of bending in a dorsal direction in our study and a caudal
direction in the study of Pooya et al. The uniform failure of the bone plate in the latter study suggests that caudal prebending of the bone plate at the level of the distal graft–radial carpal bone interface may weaken the plate and predispose to plate failure in a caudal direction at this location. Bone plate application without prebending may minimize the risk of this mode of failure. However, regardless of the mode and site of failure, bone plate deformation in limbs reconstructed with cortical bone grafts still occurred at approximately the same rate in both studies.

In contrast, bone plate and construct failure occurred less commonly in limbs reconstructed with an endoprosthesis. The significantly greater yield and ultimate strength of the endoprosthesis in axial loading frequently resulted in failure of the potted humerus rather than the construct. In combination with the stiffness data, these findings suggest the endoprosthesis is a suitable material for limb-sparing surgery of the canine distal antebrachium and that clinical use of an endoprosthesis may be associated with a decreased risk of implant failure, especially in acute loading situations. An important consideration is that this first-generation endoprosthesis is designed as a spacer and does not support osseous integration between the host bone and implant. As a result, long-term cyclic loading may cause bone resorption at the endoprosthesis–bone interface resulting in increased loads being transmitted through the bone plate and screws, thus predisposing to implant failure. Further clinical or biomechanical studies are required to evaluate the effects of long-term cycling on the performance of this endoprosthesis.

Role of the Ulna

The role of the ulna in providing biomechanical stability to the reconstructed antebrachium has not been investigated. We hypothesized that preservation of the ulna would not improve the biomechanical performance of limbs reconstructed with either an endoprosthesis or cortical bone graft in axial loading. This was hypothesized because loads are transmitted through diarthrodial joints, such as the antebrachiocarpal joint, across contact areas. The contact area between the distal ulna and ulnar carpal bone is small when compared with the distal aspect of the radius and radial carpal bone. Hence, the ulna contributes minimally to transmission of weight-bearing forces through the antebrachium. Preservation of the ulna did increase the load to yield and ultimate failure by 41% and 29%, respectively, in limbs reconstructed with cortical bone grafts. However, this was not significant and there were no significant differences in stiffness, yield load and energy, and ultimate load and energy at failure with preservation or resection of the ulna in either of the constructs. This finding has an important implication for the clinical management of dogs with primary bone tumors of the distal radius treated with limb-sparing surgery using techniques other than vascularized ulna autografts (e.g. cortical allograft, endoprosthesis, or intercalary bone transport).

Clinically, it can be difficult to determine whether primary bone tumors of the distal radius have extended into the adjacent ulna. Furthermore, separation of the styloid process of the ulna from the distal radius without compromising the tumor capsule can be challenging. Local tumor recurrence is reported in up to 28% of dogs after limb-sparing surgery of the distal radius and most occur in the vicinity of the preserved ulna. Our findings suggest that the ulna and radius can be resected en bloc without compromising the stability of the reconstructed limb in axial compression. En bloc resection of ulna with the radius would minimize the pre and intraoperative concerns presented by the ulna and may decrease the incidence of local tumor recurrence after limb-sparing surgery.

The endoprosthesis provides an attractive alternative to cortical allografts for reconstruction of radial defects for limb-sparing surgery in dogs. Cortical allografts are incorporated by a process called creeping substitution and this process can take > 2 years for completion. For most dogs with appendicular OSA, cortical allograft incorporation is unlikely to occur within the expected lifespan of the dog as the median survival time of dogs with appendicular OSA treated with curative-intent surgery and postoperative chemotherapy is 235–366 days. As a result, the major role of cortical allografts in limb-sparing surgery is to act as a spacer in the radial defect. The endoprosthesis also acts as a spacer and has the additional benefits of superior biomechanical performance, immediate availability, decreased risk of infectious disease transmission, and avoidance of problems commonly associated with cortical allografts, such as bone harvesting and banking. Future considerations include coating the ends of the endoprosthesis with hydroxyapatite or other materials to promote osseointegration for long-term stability and the use of locking holes on the limb-sparing plate to reduce the risk of implant pullout and improve construct stability.

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REFERENCES


