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Comparison of cross-sectional geometrical properties and bone density of the proximal radius between Saint Bernard and other giant breed dogs

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Abstract

Objective: To compare the geometrical properties and bone mineral density (BMD) of the proximal radius between Saint Bernard and other giant breed dogs.

Study design: Observational, cross-sectional, descriptive study.

Animals: Thirteen client-owned Saint Bernard dogs and 13 other client-owned giant breed dogs.

Methods: Computed tomography (CT) studies of Saint Bernard and other giant breed dogs were reviewed. Multiplanar reconstruction of the CT images was used to determine cross-sectional variables at the proximal half of the radius, including mean cortical thickness (mCT) and moment of inertia (MOI). Cortical BMD was estimated from Hounsfield unit measurements at each cross-section and averaged per bone. One-way analysis of variance was used to detect differences between groups.

Results: Proximal radii of Saint Bernard dogs had a lower cortical/medullary ratio (1.75 vs 2.2, $P < .001$), mCT (1.96 vs 2.64 mm, $P < .001$), and MOI in all planes (mediolateral [ML]: 2086.09 vs 2757.69 mm^4, $P < .001$; craniocaudal [CrCd]: 3736.36 vs 4370.28 mm^4, $P = .025$; and polar: 5852.45 vs 7127.97 mm^4, $P = .002$) compared with bones of other breeds. Cross-sectional BMD did not differ between groups of dogs, but the mean BMD of all cross-sections was lower in Saint Bernard dogs (1214.27 vs 1289.80 mg/mm^3, $P = .029$).

Conclusion: The proximal radii of Saint Bernard dogs had thinner cortices and lower CrCd, ML, and polar MOI compared with corresponding bones in giant breed dogs.

Abbreviations: ANOVA, analysis of variance; BMD, bone mineral density; BMD_{caud}, BMD caudal cortex; BMD_{cran}, BMD cranial cortex; BMD_{lat}, BMD lateral cortex; BMD_{med}, BMD medial cortex; BW, body weight; C_{caud}, caudal cortex; C_{cran}, cranial cortex; C_{lat}, lateral cortex; C_{med}, medial cortex; CrCd, craniocaudal; CSA, cross-sectional area; CT, computed tompgraphy; H, medullary cavity area; HU, Hounsfield unit; mBMD, mean cross-sectional BMD; mCT, mean cortical thickness; MOI, moment of inertia; MOI_{CrCd}, craniocaudal moment of inertia; MOI_{ML}, mediolateral moment of inertia; MOI_P, polar moment of inertia; OSA, osteosarcoma; ROI, region of interest; S, cortical area; S/H, cortical/medullary cavity ratio.

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Clinical significance: The structural properties of the proximal radius of the Saint Bernard differ from those in other giant breeds and could reduce the ability of this region to sustain biomechanical loads. These properties could predispose Saint Bernard dogs to complications after surgical limb-sparing procedures.

1 | INTRODUCTION

The Saint Bernard has been reported as one of the breeds with the highest risk for osteosarcoma (OSA).[1] The giant nature of the breed and morphologic skeletal properties have been previously associated with an increased postoperative risk after certain orthopedic interventions.[2] In addition, according to clinical observations of the authors, the Saint Bernard possesses specific geometrical and morphometric bone properties which may lead to a greater risk of developing biomechanical complications after surgical limb sparing of the distal aspect of the radius.[3] Understanding the nature and magnitude of these breed-specific bone structural properties would provide valuable information regarding how to modify implants and surgical procedures to reduce the risk of complications associated with them.

Physical characteristics such as composition and geometry are important factors in the mechanical properties and behavior of structures, including long bones. Structural properties such as cortical thickness, cortical/medullary cavity ratio, and moment of inertia (MOI) have been shown to be valuable prognostic indicators for fracture risk and have been reported to predict up to 80% of bone strength.[4-6] In man, some of the best predictors for fracture load of the radius are cortical bone mass, cortical area, and cortical width.[7] The measurement of geometrical bone properties from diagnostic imaging, and more specifically computed tomography (CT), has been previously described in both the human and veterinary literature.[4,5,8,9]

Another important predictor of bone strength is bone mineral density (BMD),[10] a variable that can be used to evaluate skeletal integrity with respect to mineral content and to determine the risk for osteoporotic fractures.[11] Assessment of BMD through the measurement of Hounsfield units (HU) from CT has become a valuable tool in veterinary medicine in recent years, providing an avenue to evaluate bone quality in a noninvasive manner.[12-14] From a mechanical perspective, the rigidity and strength of long bones is determined by both the amount of mineralized tissue (ie, mineral content or BMD) and the distribution of the mineralization in space.[6]

To the best of our knowledge, there are no published data supporting the hypothesis that the long bones of Saint Bernards have reduced geometrical properties and mineralization compared with other giant breeds rendering them relatively inferior with respect to their load bearing ability. Part of the challenge of investigating this assertion resides in the difficulty of obtaining enough cadaveric samples for biomechanical testing to achieve statistical power and significance, making this approach unpractical.

The intent of this study was to concentrate on the clinical impression that, with distal radial limb sparing, the proximal aspect of the radius is more susceptible to biomechanical complications in the Saint Bernard. As such, we sought through this study to compare the geometrical properties and BMD of the proximal radius between Saint Bernard and other giant breeds. We hypothesized that the mean cortical thickness, cortical/medullary cavity areas ratio, and MOI of the Saint Bernard radii would be reduced compared with other giant breeds. Our second hypothesis stated that the mean cross-sectional BMD values of the Saint Bernard radii would be reduced compared with other giant breeds.

2 | MATERIALS AND METHODS

2.1 | Case selection

This was an observational, cross-sectional, and descriptive study. The diagnostic imaging database at the Colorado State University Veterinary Teaching Hospital was searched for studies of client-owned dogs that underwent CT scan between 2010 and 2018. Medical records and the diagnostic imaging report previously generated by the board-certified radiologist who evaluated the study were reviewed. Data collected included signalment, diagnoses, body weight (BW) at the time of the study, reason for CT, and extent of the primary lesion when present in the measured radius.

Inclusion criteria were skeletally mature (>24 months of age) Saint Bernard and other giant breed dogs (defined as BW >45 kg)[15] with diagnostic imaging studies (helical CT, Gemini Time-of-Flight Big Bore PET/CT instrument; Phillips, Andover, Massachusetts) that were performed with 1 to 2-mm-thick slices and were between 512 × 512 and 1024 × 1024 pixels in size, kVp 120, mAs 250, with a median field of view of 50 cm (range 14.3-60), in which the radius of one or both forelimbs was completely included in the scan. Exclusion criteria included bone lesions affecting the proximal 60% of the radial length, presence of implants, or previous history of radial fractures. The selected studies were assigned to either the Saint Bernard or the control group, which comprised the other giant breeds.

2.2 | Quantitative assessment of CT images

Image analysis of the CT data was performed with a free open source DICOM viewer (Horos V3.2.1, OsiriX, horosproject.org). Measurements were performed by using a three-dimensional multiplanar reconstruction of the previously acquired CT dataset. The measurements were taken from the two-dimensional axial viewport. The craniocaudal (CrCd) axis was determined on the frontal viewport, and the mechanical axis was defined as the line passing through the center of the radial head and the center of the interfossa ridge.[4,16] The mediolateral (ML) axis was determined on the sagittal viewport, and the radial length was measured from the center of the radial head to the center of the distal radial articular concavity by using the linear ruler. After determining the ML and CrCd axis, the location of the medial, lateral cranial, and caudal cortices was determined on the axial viewport (Figure 1). Axial cross-sections through the radius were analyzed at 50%, 60%, 70%, and 80% of the distal to proximal length of the radius (Figure 2). A series of measurements for each cross-section was manually obtained: ML diameter; CrCd diameter; and thickness of the medial (C_{med}), lateral (C_{lat}), cranial (C_{cran},) and caudal (C_{caud}) cortices (Figure 3). In addition, the region of interest (ROI) tool was used to measure HU at the midpoint of the C_{med}, C_{lat}, C_{cran}, and C_{caud} (Figure 4). Radial length and cross-sectional measurements

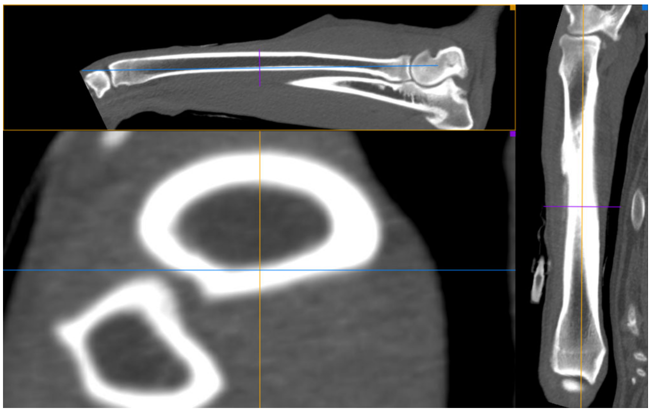

FIGURE 1 Three-dimensional multiplanar reconstruction of computed tomography data to determine craniocaudal and mediolateral axis on the frontal (right) and sagittal (upper left) viewports

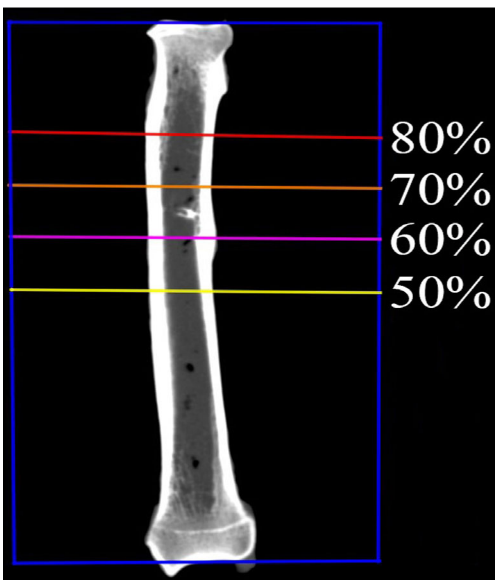

FIGURE 2 Computed tomography image of a canine radius illustrating the axial cross-sections at 50%, 60%, 70%, and 80% of the total radial length used for determination of geometrical properties and mineral density

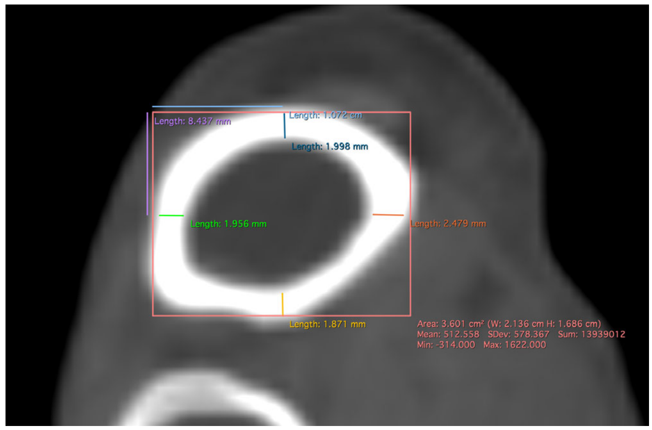

FIGURE 3 Cross-sectional measurements for mediolateral diameter and cranial-caudal diameter (pink square), thickness of the medial (orange), lateral (green), cranial (blue), and caudal (yellow) cortices. Cortical thickness measurements were performed at the midpoint (radius) of the mediolateral (light blue) and craniocaudal (purple) diameters. Measurements are presented in millimeters

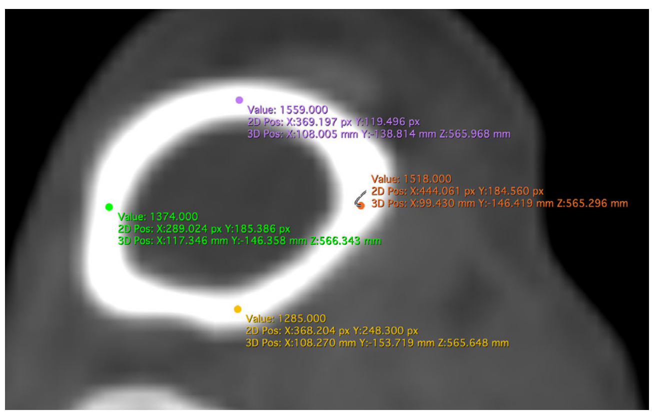

FIGURE 4 Bone mineral density was estimated from Hounsfield unit measurement at the cranial (purple), caudal (yellow), medial (orange), and lateral (green) cortices. A mean cross-sectional BMD was calculated

were taken at a consistent magnification (sagittal viewport at 350% and axial viewport at 3000%, respectively) across all dogs on the bone algorithm (window level 300 HU, window width 1500 HU). All measurements were performed by the same investigator (S.M.).

2.3 | Calculation of geometrical variables and BMD

From the measured values for diameter and cortical thickness for each cross-section, the outer cortical area (S), inner medullary cavity area (H), and cross-sectional area (CSA) were calculated as well as the cortical/medullary cavity area ratio (S/H). In addition, the mediolateral moment of inertia (MOI_{ML}), craniocaudal moment of inertia (MOI_{CrCd}), polar moment of inertia (MOI_P), and mean cortical thickness (mCT) were calculated as previously described (Appendix 1 and 2).[4,8]

From the measured HU, the BMD (milligrams/centimeters cubed) was estimated with the use of a customized mineral reference phantom (Computerized Imaging Reference Systems, Norfolk, Virginia) that contained multiple calibration objects with different densities (between 400 and 1750 mg/cm^3 calcium hydroxyapatite) and a phantom-derived linear regression equation, as previously described.[11,13,17] The HU values were converted to BMD for the medial, lateral, cranial and caudal (BMD_{med}, BMD_{lat}, BMD_{cran} and BMD_{caud}, respectively), cortices and a mean cross-sectional BMD (mBMD) was calculated. The mean value from all combined cross-sections (50%, 60%, 70%, and 80%) for all geometrical values and BMD was calculated and compared between the two groups.

2.4 | Statistical analysis

The mean (±SD) of each value evaluated from each cross-section and the mean (±SD) from all cross-sections combined were calculated Excel 2016 (Microsoft, Redmond, Washington). One-way analysis of variance (ANOVA) was used to detect differences between the measured (C_{med}, C_{lat}, C_{cran}, C_{caud}) and calculated (S, H, S/H, CSA, mCT, MOI_{ML}, MOI_{CrCd}, MOI_P) geometrical values as well as the BMD values (BMD_{med}, BMD_{lat}, BMD_{cran}, BMD_{caud}, and mBMD) between the Saint Bernard and the control groups (for each cross-section and for all cross-sections combined). Statistical power for each comparison was calculated in OpenEpi (Open Source Epidemiologic Statistics for Public Health, Version 3.01; https://www.openepi.com/Menu/OE_Menu.htm).[18] One-way ANOVA (for age, BW, and radial length) and χ^2 (for sex) were used to detect differences between the two groups. The ANOVA was validated by using the test for equal variances and normality. $P \leq .05$ was considered significant.

3 | RESULTS

Twenty-six CT studies were included in this study. The Saint Bernard group (n = 13) comprised nine neutered males and four spayed females with a median age of 7 years (range, 4-10) and a median BW of 62.38 kg (range, 47.1-83.1). The control group (n = 13) included Mastiffs (3), Bernese mountain dogs (2), Great Danes (2), Rottweilers (2), Irish wolfhound (1), Leonberger (1), Newfoundland (1) and Swiss mountain dog (1). There were seven neutered males, four spayed females, and two intact males, with a median age of 6 years (range 2-9) and a median BW of 60.1 kg (range 48-90.3). Mean radial length was 216.77 mm (±13.02) for the Saint Bernard group and 225.31 mm (±30.5) for the control group. No differences were found between the Saint Bernard group and the control group when comparing for sex ($P = .17$), age ($P = .09$), weight ($P = .78$), and radial length ($P = .36$).

Indications for CT for the dogs in the Saint Bernard group included right radial distal OSA (n = 5), left radial distal OSA (4), right humeral OSA (1), left humeral OSA (1), right mandibular OSA (1), and left maxillary soft tissue sarcoma (1). Indications for CT for the dogs in the control group included right radial distal OSA (n = 5), left radial distal OSA (5), right humeral OSA (1), mast cell tumor distal left front limb (1), and left angular limb deformity (1; right radius was included in study).

There were differences in all cross-sections for several variables. For all cross-sections, C_{lat}, C_{cran}, C_{caud}, CSA, S/H, and mCT were reduced in the Saint Bernard. All variables except S were reduced in the Saint Bernard at the 80% cross-section and for the mean value of all combined cross-sections. In addition, there were differences between groups in MOI_{CrCd} at one of the cross-sections, in MOI_{ML}, and in MOI_P at two of the cross-sections. The 80% cross-section had all three MOI reduced for the Saint Bernard; this was also consistent for the mean value from all combined cross-sections for all three MOI (Table 1).

There were no differences in cross-sectional BMD values between groups, while there was a difference between the mean value from all combined cross-sections for BMD_{lat}, BMD_{cran}, BMD_{caud}, and mBMD (Table 2).

4 | DISCUSSION

The main finding of our study was that the population of Saint Bernard dogs tested had thinner cortices and lower MOI than other giant breed dogs. In addition, the averaged data from all cross-sections for the Saint Bernard dogs had a lower BMD than other giant breed dogs. The difference in structural properties of the proximal radius between the Saint Bernard and other giant breeds could reduce the ability of this region

TABLE 1 Geometrical values, statistical significance, and power for each comparison

TRL, %	Dogs	C_{med}	C_{lat}	C_{cran}	C_{caud}	S, mm^2	H, mm^2	CSA, mm^2	S/H	mCT, mm	MOI_{ML}, mm^4	MOI_{CrCd}, mm^4	MOI_P, mm^4
50%	Saint Bernard, mean (±SD)	2.96 (0.92)	2.33 (0.44)	1.97 (0.40)	1.83 (0.43)	251.65 (38.02)	142.53 (34.33)	109.12 (21.30)	1.81 (0.27)	2.16 (0.42)	2540.75 (849.50)	4625.45 (1332.51)	7166.21 (2077.34)
	Control group, mean (±SD)	3.26 (0.69)	2.86 (0.56)	2.51 (0.51)	2.43 (0.60)	249.79 (44.80)	120.03 (29.97)	129.77 (25.03)	2.14 (0.34)	2.66 (0.44)	3132.82 (1408.70)	4858.22 (1467.70)	7991.05 (2746.70)
	P-value (power %)	.347 (15.39)	.013* (76.53)	.006* (85.18)	.007* (83.42)	.910 (2.27)	.088 (42.87)	.033* (62.00)	.013* (78.25)	.006* (84.23)	.207 (25.40)	.676 (5.92)	.396 (48.04)
60%	Saint Bernard, mean (±SD)	2.74 (0.97)	2.46 (0.41)	1.87 (0.40)	1.67 (0.39)	236.25 (35.80)	135.59 (36.68)	100.66 (15.05)	1.81 (0.32)	2.05 (0.37)	2099.36 (575.37)	4223.14 (1218.78)	6322.50 (1539.67)
	Control group, mean (±SD)	3.00 (0.83)	3.04 (0.66)	2.55 (0.37)	2.46 (0.53)	246.17 (33.59)	117.02 (23.67)	129.15 (19.47)	2.14 (0.28)	2.66 (0.37)	2992.83 (972.45)	4813.67 (1236.30)	7806.50 (1976.10)
	P-value (power %)	.470 (10.96)	.013* (76.78)	<.001* (99.45)	<.001* (99.11)	.473 (10.85)	.138 (33.50)	<.001* (98.66)	.011* (79.91)	<.001* (98.76)	.009* (81.36)	.232 (23.17)	.043* (56.99)
70%	Saint Bernard, mean (±SD)	2.46 (0.89)	1.98 (0.40)	1.89 (0.31)	1.49 (0.37)	224.81 (32.66)	134.92 (32.20)	89.89 (13.97)	1.70 (0.21)	1.87 (0.32)	1972.90 (561.80)	3367.29 (956.53)	5340.18 (1229.43)
	Control group, mean (±SD)	2.90 (0.40)	2.85 (0.56)	2.86 (0.37)	2.19 (0.44)	225.26 (40.83)	104.49 (27.38)	120.77 (19.77)	2.20 (0.27)	2.62 (0.32)	2593.21 (1040.22)	4071.92 (1518.33)	6665.13 (2258.91)
	P-value (power %)	.117 (36.92)	<.001* (99.53)	<.001* (100)	<.001* (99.25)	.975 (1.40)	.016* (73.76)	<.001* (99.58)	<.001* (99.95)	<.001* (100)	.071 (47.29)	.170 (29.32)	.076 (45.92)
80%	Saint Bernard, mean (±SD)	2.08 (0.69)	1.81 (0.40)	1.58 (0.34)	1.77 (0.45)	211.21 (29.95)	129.50 (32.48)	81.71 (14.27)	1.67 (0.23)	1.75 (0.35)	1731.36 (544.88)	2849.55 (669.10)	4580.91 (941.73)
	Control group, mean (±SD)	3.14 (0.72)	2.79 (0.39)	2.71 (0.45)	2.29 (0.39)	213.77 (36.63)	96.99 (28.83)	116.78 (14.28)	2.31 (0.44)	2.63 (0.30)	2311.89 (711.71)	3737.30 (1376.49)	6049.19 (1839.01)
	P-value (power %)	.001* (96.94)	<.001* (100)	<.001* (100)	.004* (88.27)	.847 (3.14)	.013* (77.01)	<.001* (100)	<.001* (99.64)	<.001* (100)	.028* (64.63)	.047* (55.23)	.017* (72.66)
Mean	Saint Bernard, mean (±SD)	2.56 (0.87)	2.14 (0.41)	1.83 (0.36)	1.69 (0.41)	230.98 (34.11)	135.64 (33.92)	95.34 (16.15)	1.75 (0.26)	1.96 (0.36)	2086.09 (692.74)	3766.36 (1258.60)	5852.45 (1764.30)
	Control group, mean (±SD)	3.08 (0.66)	2.89 (0.54)	2.66 (0.42)	2.34 (0.49)	233.75 (38.96)	109.63 (27.46)	124.12 (19.64)	2.20 (0.33)	2.64 (0.36)	2757.69 (1082.00)	4370.28 (1445.81)	7127.97 (2312.76)
	P-value (power %)	.001* (91.28)	<.001* (100)	<.001* (100)	<.001* (100)	.716 (5.15)	<.001* (99.01)	<.001* (100)	<.001* (100)	<.001* (100)	<.001* (96.48)	.025* (62.25)	.002* (88.53)

Abbreviations: C_{caud}, caudal cortex; C_{cran}, cranial cortex; C_{lat}, lateral cortex; C_{med}, medial cortex; CSA, cross-sectional area; H, medullary cavity area; mCT, mean cortical thickness; MOI_{CrCd}, craniocaudal moment of inertia; MOI_{ML}, mediolateral moment of inertia; MOI_P, polar moment of inertia; S, cortical area; S/H, cortical/medullary cavity ratio; TRL, total radial length.

*$P < .05$.

TABLE 2 Calculated BMD, statistical significance, and power for each comparison[a]

TRL	Dogs	BMD_{med}	BMD_{lat}	BMD_{cran}	BMD_{caud}	mBMD
50%	Saint Bernard, mean (±SD)	1313.02 (238.22)	1284.25 (152.88)	1251.49 (209.27)	1185.76 (185.60)	1258.63 (182.14)
	Control group, mean (±SD)	1321.68 (156.54)	1307.40 (121.74)	1369.27 (192.58)	1259.54 (143.09)	1314.47 (141.09)
	P-value (power %)	.9136 (2.22)	.6731 (5.97)	.1484 (32.04)	.2675 (20.48)	.3908 (13.85)
60%	Saint Bernard, mean (±SD)	1358.98 (345.82)	1259.54 (163.88)	1264.69 (255.68)	1165.45 (203.08)	1262.16 (218.40)
	Control group, mean (±SD)	1260.35 (164.73)	1301.78 (105.71)	1370.15 (185.15)	1252.70 (214.84)	1296.25 (144.86)
	P-value (power %)	.3625 (15.10)	.4425 (11.88)	.2401 (22.50)	.2978 (18.52)	.6434 (6.56)
70%	Saint Bernard, mean (±SD)	1204.10 (215.39)	1177.63 (161.19)	1248.17 (232.78)	1095.05 (211.00)	1181.24 (193.70)
	Control group, mean (±SD)	1282.1 (131.29)	1285.13 (117.43)	1407.58 (162.07)	1176.42 (245.33)	1287.82 (148.39)
	P-value (power %)	.2756 (19.93)	.0638 (49.35)	.0540 (52.65)	.3736 (14.59)	.1284 (35.01)
80%	Saint Bernard, mean (±SD)	1124.43 (260.88)	1184.88 (166.49)	1189.62 (256.22)	1121.25 (166.87)	1155.04 (202.35)
	Control group, mean (±SD)	1255.48 (140.03)	1260.96 (159.57)	1332.78 (183.26)	1193.41 (168.47)	1260.66 (152.89)
	P-value (power %)	.1236 (35.79)	.2458 (22.06)	.1143 (37.40)	.2834 (19.42)	.1463 (32.34)
Mean	Saint Bernard, mean (±SD)	1250.13 (265.08)	1226.58 (161.11)	1238.49 (238.49)	1141.88 (191.64)	1214.27 (199.15)
	Control group, mean (±SD)	1279.92 (148.15)	1288.82 (126.11)	1369.95 (180.76)	1220.52 (192.93)	1289.80 (146.81)
	P-value (power %)	.4954 (10.02)	.0314* (58.78)	.0017* (89.74)	.0396* (54.97)	.0289* (60.09)

Abbreviations: BMD, bone mineral density; BMD_{caud}, BMD caudal cortex; BMD_{cran}, BMD cranial cortex; BMD_{lat}, BMD lateral cortex; BMD_{med}, BMD medial cortex; mBMD, mean cross-sectional BMD; TRL, total radial length.

[a]BMD is expressed in mg calcium hydroxyapatite/mm^3.

*$P < .05$.

to sustain biomechanical loads and predispose the breed to complications after surgical limb-sparing procedures.

Moment of inertia values are useful predictors of bone strength across different planes. The MOI is a critical component with respect to the resistance of a structure to bending deformation. The larger the MOI_P is, the greater is the bone resistance to torsional forces, while larger MOI_{CrCd} and MOI_{ML} values indicate a greater bone resistance to bending forces in the CrCd and ML planes, respectively.[19] Therefore, the lower values obtained for MOI_{ML}, MOI_{CrCd}, and MOI_P in the Saint Bernard dogs could be an indicator of an increased risk of spiral fractures due to torsional forces as well as diaphyseal fractures due to bending forces in the ML and CrCd planes compared with other large breed dogs. It is worth noting that, while the values for MOI were lower for the Saint Bernard, the power for this cross-sectional comparison was lower than the common cutoff of 80%; therefore, these results should be interpreted with caution.

While there was no difference in mean BMD for each of the cross-sections (and therefore our second hypothesis was not supported by the data), we found a difference in the mean of the calculated values for all cross-sections. Such statistical findings may be explained by the relatively small samples for each of the cross-sections, as indicated by the low power in most of the comparisons, although pooling and analyzing the data together resulted in statistical significance. This finding may be due to the fact that the mean values provide a more comprehensive evaluation of the entire bone as opposed to the individual cross-sectional measurements. It is alternatively possible that the significance that was detected when the means of the pooled data were compared was a type I statistical error. Although age, weight, and radial length were not different between the two groups, the lack of differences may be associated with a low power of testing. Thus, the findings should be interpreted with caution because of the small sample.

Our study was limited to the proximal aspect of the radius because of the authors' previous experience and perception that the Saint Bernard breed is at higher risk of mechanical complications after limb-sparing surgical procedures. Most CT studies available to collect data were from dogs with distal radial OSA, which was considered appropriate because they were representative of the population of dogs we wanted to study. This study was not designed to determine the effect of a distal radial primary tumor on the proximal aspect of the bone, although it seems unlikely that a distally located tumor could alter the geometrical values of the remaining unaffected bone proximally. However, it is possible that a pathologic condition on the same limb could affect either cortical thickness due to microscopic bone lysis or BMD by means of disuse osteopenia.

A mixture of giant breed dogs was selected as a control group rather than another representative large breed to control variables such as age, weight, and radial length. Eliminating BW as a potential confounding factor was important because increases in animal mass have been associated with altered distribution of bone tissue away from the cross-sectional centroid.[5] Such change increases the MOI by maintaining a constant width of cortices and affecting the S/H ratio.[5] Normalizing the measured and calculated geometrical values by radial length or weight prior to analysis was not performed because there were no differences in radial length or BW between the two groups.

Bone specimens were not available for in vitro biomechanical testing in our study, so the findings derived from the CT data could not be correlated with mechanical testing results. However a strong correlation between CT-derived geometrical indices, such as $MOI_{CrCd,}$ and the yield and maximum force tested in vitro in canine bones with OSA, has been documented.[20] A high correlation between BMD measured via CT and compressive strength from biomechanical testing in the human radius has also been reported.[21] These findings are clinically relevant because they may serve as a basis to modify procedures, implants, and postoperative recovery guidelines to account for these structural differences in Saint Bernard dogs and, more specifically, for surgical limb-sparing interventions. Future prospective studies are warranted to correlate the findings of this investigation with the rates of postoperative complications and fractures after complex orthopedic procedures in the Saint Bernard breed.

Although the findings of this study were limited to the proximal radius, these differences in cortical thickness and associated geometrical values have the potential to be a general feature across the Saint Bernard bones. These findings should be considered when evaluating Saint Bernard dogs as possible donors for bone allografts. Additional studies are warranted to determine whether these structural differences are evident across all long bones in the Saint Bernard breed.

The present study was limited by the fact that measurements were taken from only the proximal portion of the bones because most of these dogs were affected by distal radial OSA. While the images were carefully examined to verify that on the CT images the distal lesion did not extend farther than 40% of the distal-proximal length on the affected bones, it is impossible to know with certainty that the bone at this distance was not affected at the microscopic level or how this could alter the cortical thickness or BMD.

Another limitation of this study, as with other similar studies,[4,8] is that the calculations to derive the values S, H, and CSA make the assumption that the cross-section of the radius is an ellipse (especially as cross-sections extend into the proximal portion where it becomes more of a rectangular shape), which is only an approximation of its true shape. In addition, the spatial arrangement of the transverse sections evaluated relative to one another were not taken into account. Therefore, the impact of the three-dimensional morphology of the bone was not assessed (ie, curvature of the proximal aspect of the radius in both the ML and CrCd planes). For example, the effect of angular differences in the proximal aspect of the radius were not evaluated by the methods of this type of study. The fact that the measurements were performed by a single nonblinded investigator is a significant limitation, and, while this was elected to maintain repeatability of the methodology and avoid interobserver variability, this should be taken into consideration when interpreting the results of this study. Finally, the use of a "point" ROI tool rather than an elliptical or circular measurement of HU is another limitation because the former may be associated with a higher degree of variability than the latter.

In conclusion, the proximal radii of Saint Bernard dogs in this study had thinner cortices and lower CrCd, ML, and polar MOI compared with corresponding bones in giant breed dogs. These structural differences could reduce the ability to support ML and CrCd bending as well as torsional forces and increase the risk of complications after surgical limb-sparing procedures. The lower BMD detected in the bones of Saint Bernard dogs when all cross-sectional data were combined provides additional evidence to support a predisposition to fracture of these bones. However, the clinical relevance of this finding requires additional investigation.

CONFLICT OF INTEREST

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

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APPENDIX 1: DERIVATION OF EXPRESSIONS

Derivation of expressions:[4,8]

$$a = \frac{A}{2.}$$
$$b = \frac{B}{2}$$
$$c = a - \frac{Cmed + Clat}{2} d = b - \frac{Ccran + Ccaud}{2}$$

S is defined as the outer cross-sectional area, while H is defined as the inner cross-sectional area (medullary cavity):

$$S = \pi ab$$
$$H = \pi cd$$

A is mediolateral diameter; a is mediolateral radius; B is craniocaudal diameter; b is craniocaudal radius.

The following are the equations required for the calculation of MOI.

The coordinates of the center of H are:

$$X_H = a - (C_{lat} + c)$$
$$Y_H = b - (C_{cran} + d)$$
$$X_0 = -\frac{H}{S-H}\,[a - (C_{lat} + c)]$$
$$Y_0 = -\frac{H}{S-H}\,[b - (C_{cran} + d)]$$
$$\mathrm{MOI_{ML}} = \pi\, a\, b\, (\frac{b\hat{}2}{4} + Y_0^2) - \pi\, c\, d\, [\frac{d\hat{}2}{4} + (Y_H - Y_0)^2]$$
$$\mathrm{MOI_{CrCd}} = \pi\, a\, b\, (\frac{a\hat{}2}{4} + X_0^2) - \pi\, c\, d\, [\frac{c\hat{}2}{4} + (X_H - X_0)^2]$$
$$\mathrm{MOI_P} = \mathrm{MOI_{ML}} + \mathrm{MOI_{CrCd}}$$
$$\mathrm{mCT} = \frac{1}{2\pi}\sqrt{\frac{(CSA)\hat{}3}{Ip}}$$

APPENDIX 2: MEASUREMENT OF PARAMETERS ON CT IMAGE