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Biomechanical characteristics of regenerated cortical bone in the canine mandible

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Abstract

To test the mechanical properties of regenerate cortical bone created using Mandibular Bone Transport (MBT) distraction, five adult male American foxhound dogs underwent unilateral distraction of the mandible with a novel MBT device placed to linearly repair a 30-35 mm bone defect. The animals were sacrificed 12 weeks after the beginning of the consolidation period. Fourteen cylindrical specimens were taken from the inner (lingual) and outer (buccal) plates of the reconstructed mandible and 21 control specimens were removed from the contralateral aspect of the mandible. The mechanical properties of the 35 cylindrical cortical bone specimens were assessed by using a non-destructive pulse ultrasound technique. Results showed that all of the cortical mechanical properties exhibit higher numerical values on the control side than the MBT regenerate side. In addition, both densities and the elastic moduli in the direction of maximum stiffness of the regenerate cortical bone specimens are higher on the lingual side than the buccal side. Interestingly, there is no statistical difference between elastic modulus (E_1 and E_2) in orthogonal directions throughout the 35 cortical specimens. The data suggest that the regenerate canine cortical bone is not only heterogeneous, but the elastic mechanical properties tend to approximate transverse isotropy at a tissue level as opposed to control cortical bone that is orthotropic. In addition, the elastic mechanical properties are not only higher on the control side but also in the lingual anatomical position, suggesting a stress shielding effect from the presence of the reconstruction plate.

Keywords

Ultrasound technique; animal model; bony tissue; bone transport; distraction device; bone healing; jaw mechanics

1. Introduction

Bone transport distraction osteogenesis is a surgical technique in which a bony disc is moved within a segmental defect to fill the gap with new bony tissue (Sacco and Chepeha,

2007). Over the past decade, mandibular bone transport (MBT) has been an alternative procedure to repair mandibular segmental defects produced by trauma and oncology resections (Kuriakose et al., 2003). MBT is able to achieve mandibular reconstruction in a predictable way, with few complications (Imola et al., 2002), less complexity than other procedures (Rubio-Bueno et al., 2000), and minimal tissue morbidity (Karp et al., 1990). However, assessing the biomechanical quality of the newly formed cortical bone after MBT is important to evaluate the success of the distraction process (Li et al., 2002), to define the best time for the endpoint of the consolidation period (Claes and Cunningham, 2009), to determine the optimal time for the removal of the MBT device (Orbay et al., 1992), and also to better understand the relationship between mechanical properties and microstructure (Robertson and Smith, 1978; Lipson and Katz, 1984). This knowledge will help to advance understanding the biomechanical behavior of the mandible after MBT by supporting the definition of accurate numerical models gained from the finite element method (FEM) (Castaño et al., 2002; de Zee et al., 2007).

Although, in our knowledge, no previous studies have reported the mechanical properties of the new bony tissue obtained after MBT, several attempts to obtain the differences in mechanical properties between newly formed bone after monofocal distraction osteogenesis and mature bone have been made. The first report of canine mechanical properties after distraction osteogenesis was presented by Orbay and coworkers in 1992. They examined the torsional properties of canine tibial bones at 4, 6, 8, and 10 weeks after the completion of monofocal distraction and found great variability in mechanical properties over time (Orbay et al., 1992). The same year, Schickendantz and coworkers tested canine tibial bones after monofocal distraction by using torsional load tests and found that several regenerate bone samples were as strong as the control tibial bones (Schickendantz et al., 1992). The first distracted mandibular bone strength test was performed in a unilateral bifocal distraction experiment by Costantino and coworkers in 1993. They performed a three point bending test of the mandibular bone from three mongrel dogs at four different sites: a control reference from the contralateral untreated hemimandible, the docking site, the transport disc, and the newly grown bone. They found the average ultimate strength of the regenerate specimens was 77% of the strength of the control specimens after 56 weeks of consolidation and mineralization. However, due to the small sample size and high variability, the results were not significant (Costantino et al., 1993). Walsh and coworkers in 1994 suggested that mechanical properties of the regenerate bone increased with time until reaching 50% of the tensile properties of the original cortical bone in the canine tibia after a 12 weeks consolidation period (Walsh et al., 1994). Fitch and coworkers in 1996 evaluated the biomechanical properties of regenerate canine tibial cortical bone using a cantilever-bending test. They found that the bending stiffness of the new bone by day 79 (13 weeks) was 37-46%, which was significantly less than the control bone (Fitch et al., 1996). Kunz and coworkers in 2006 evaluated mechanical properties of the regenerated bone by performing a compression test of mandibular cortical bone specimens obtained after a bilateral distraction process in a canine model (Kunz et al., 2006). They found that the regenerate bone was 62.5% as stiff as the control bone after a 13 week consolidation period.

Although all the previous reported attempts to search for differences between regenerate cortical bone and control cortical bone after mandibular distraction osteogenesis have assumed the cortical bone as an isotropic material (mechanical properties present no variability by direction) (Ashman et al., 1985), we have assumed the anisotropic possibility for regenerate and control cortical bone by using an ultrasonic wave technique that enables determination of elastic coefficients in 3D by measuring the multiple velocities of ultrasonic waves through cylindrical cortical specimens in controlled directions to characterize their elastic properties (Ashman et al., 1984; Schwartz-Dabney and Dechow, 2003). The purpose of this study is to test the hypotheses that the elastic properties in canine mandibular

regenerate and control cortical bone at a tissue level are (1) heterogeneous relative to each other, but (2) can both be approximated as similarly orthotropic.

2. Material and Methods

Five adult male American foxhound dogs, weighing 60 to 94 lbs, approximately two years old, underwent MBT by creating a 30-35 mm unilateral mandibular defect. The jaw was then stabilized with a novel reconstruction plate to which an internal transport distraction unit was attached (Fig. 1). After seven days of latency, the device was activated at a rate of 1 mm/day for 4-5 weeks. Half-way through the distraction period, molars were extracted on the contralateral control side of the mandible, creating an approximately 30 mm long edentulous control ridge. Once distraction was accomplished on the experimental side, the regenerate bone was allowed to consolidate for six weeks before placement of dental implants on both the experimental and control sides. After a healing period of six weeks, the animals were sacrificed and their mandibles were dissected. The mandibles were stored at -20°C prior to removal of bone specimens to ensure that the bone's elastic properties were preserved (Zioupus P, 2000).

Thirty-five cylindrical cortical bone specimens (mean diameter=5.93 mm, SD=0.06 mm; cortical thickness=2.72 mm, SD=0.24 mm) were removed from the lingual and buccal cortices of the regenerate and control sides of the mandible through the use of a low-speed dental drill continuously cooled with a water drip. Twenty-one cylindrical cortical specimens were taken from the control sides, and fourteen from the regenerate sides (Table 1). Prior to removal, each bone specimen was marked with a graphite line parallel to the lower border of the mandibular corpus, indicating the anatomical orientation. After extraction, all the cortical samples were stored in a 50:50 solution of 95% ethanol and isotonic saline at room temperature (19°C) to maintain the elastic properties of cortical bone with minimal changes over time (Ashman et al., 1984). Cortical bone apparent density (mg/cm³) was calculated from sample weights taken with an analytical balance (PM460, Mettler-Toledo International INC, Columbus, OH, USA) according to Archimedes' principle of buoyancy (Ashman et al., 1984).

Three orthogonal principal axes of stiffness were defined within each cortical specimen by placing the cylindrical cortical specimens between two ultrasonic longitudinal transducers (Olympus V312, immersion, 0.25 in diam., Waltham, MA, USA), that sent 10MHz ultrasonic pulses through the specimens (Schwartz-Dabney and Dechow, 2003). Ultrasonic velocities were calculated by dividing either the specimen thickness or specimen diameter by the time delay. The time delay is the difference between the start of the transmitted wave applied to one side of the specimen and the start of the received ultrasonic signal at the other side of the specimen (Ashman et al., 1984). The specimens were tested in nine consecutive directions around the circumference at 22.5° intervals, starting at the graphite reference line. Then three orthogonal principal directions were defined for each cylindrical specimen with the following rule: 3 is the direction of maximum stiffness in the plane of the cortical plate, 2 is the direction of minimum stiffness in the same plane, and 1 is the direction perpendicular to the cylindrical plane of the specimen (Schwartz-Dabney and Dechow, 2003).

Elastic mechanical properties of the cortical bone were calculated from measured longitudinal and transverse (Olympus V156, 5 MHz, contact, 0.25 in diam., Olympus, Waltham, Ma, USA) ultrasonic wave velocities using the relationship between stress and strain tensors as defined in Hooke's law (Ashman et al., 1984; Rho, 1996). Notation for how the elastic mechanical properties were related to the principal axes of stiffness is as follows: the elastic modulus E is followed by a subscript indicating their corresponding principal

direction (E_1 , E_2 , E_3); the shear modulus G is followed by two subscripts indicating the principal plane of shear (G_{13} , G_{12} , G_{23}); and the Poisson's ratios ν are denoted by a double subscript indicating the principal direction of load (first subscript) followed by the orthogonal direction for Poisson's strain (second subscript) (ν_{12} , ν_{21} , ν_{23} , ν_{32} , ν_{13} , ν_{31}) (Marinescu et al., 2005). The method of calculation assumed that the cortical bone specimens are basically orthotropic in structure; a conjecture supported by the symmetry of the curves generated when plotting variation in ultrasonic velocities by orientation within each specimen. A consequence of orthotropy is that $\nu_{ij} E_i = \nu_{ji} E_j$ and thus only three Poisson ratios need to be reported: ν_{12} , ν_{13} , and ν_{23} . In addition, anisotropy was quantified in the cortical plane by using ratios of principal elastic moduli (E_2/E_3).

Data were analyzed using the SPSS statistical software (SPSS Inc, Chicago, IL) to test for differences in mechanical properties between regenerate and control mandibular cortical bone. Anovas were used to test for differences among the five dogs. Because cortical bone specimens were removed from consistent locations on both sides of the mandible, paired t-tests were used to test for differences between the buccal and lingual sides of the mandibles. Five pairs of specimens from the regenerate side of the mandible, representing three animals, and ten pairs from the control side, representing five animals, were compared (Table 1). Paired t-tests were also used to test for a difference between superior and inferior relative positions in six paired regenerate specimens from four animals, and nine paired control specimens from five animals (Table 1).

The orientation of maximum stiffness was assessed by using the circular statistical software Oriana (Kovach Computing Services, Anglesey, Wales). Tests included Rayleigh's uniformity test to determine the presence of a common orientation among specimens, as well as Watson-Williams tests to determine differences between groups.

3. Results

All the five dogs survived the entire MBT process without major surgical complications. The healing process was normal among the dog subjects without affecting feeding or physical activity. However, the third dog experienced detachment of the new tissue, which was immediately reattached; and the fourth dog reported necrosis of the transport disc, although new bony tissue was regenerated. MBT disc advance was performed without complications or apparent animal discomfort. All the subjects reached MBT reconstruction with adequate bony volume and external shape.

3.1. Density

The mean density of all the 35 cylindrical cortical bone specimens was 1883.5 ± 173.7 mg/cm³ (Table 2). No statistical differences were found among animals in density ($F=0.353$, $p=0.84$). Likewise, no significant differences in density were found in the control cortical bone between buccal and lingual sides. However, a significant difference in density was found in the regenerate bone ($p=0.009$) between buccal and lingual sides (Fig. 2A). In comparisons between mandibular locations, no significant differences in the regenerate cortical bone were found between the alveolar and basal positions. Whereas, in the control cortical bone the difference between the alveolar and basal positions (Fig. 2B) was significant ($P=0.045$). Overall, density was significantly less ($F=24.55$; $p<0.001$) in the regenerate cortical bone (1746.6 ± 183.2 mg/cm³) than in the control cortical bone (1974.8 ± 87.2 mg/cm³), (Fig. 2C).

3.2. Maximum stiffness orientation

No significant differences in maximum stiffness orientation were found between regenerate and control cortical bone, alveolar and basal positions, or lingual and buccal sides (Fig. 3A). The principal averaged circular mean direction for the 35 specimens was 12.4° with a circular standard deviation of 12.0° , and length of mean vector (r) of 0.978 (Fig. 3B). Since r is a measurement of circular dispersion, a value close to one represents a large concentration of the data around the mean.

3.3. Elastic moduli

The elastic modulus E_2 expressed statistical differences between dogs 1 and 5 ($p=0.031$); complementarily E_1 denoted statistical differences between dogs 1 and 3 ($p=0.02$) as well as dogs 1 and 5 ($p=0.015$). Although significant differences were found in elastic moduli E_1 ($p=0.03$), E_2 ($p=0.015$), and E_3 ($p=0.017$) between buccal and lingual anatomical positions on the regenerate cortical bone specimens (Fig. 4A), no significant differences were found in elastic moduli in the control cortical bone specimens (Table 2). Testing for differences between alveolar and basal positions, a statistical difference ($p=0.01$) was found for E_3 between the alveolar (29.2 ± 2.5 GPa) and basal (33.2 ± 2.6 GPa) relative positions (Table 2).

Significant differences in elastic modulus E_1 ($F=11.12$, $p=0.002$), E_2 ($F=15.04$, $p=0.001$), and E_3 ($F=23.65$, $p=0.001$) were found between regenerate and control bone specimens (Fig. 4B). Furthermore, the statistical evaluation of all thirty-five specimens showed significant differences in principal elastic moduli between directions 1 and 3 ($p=0.001$), and 2 and 3 ($p=0.001$). In contrast, no significant differences were found between directions 1 and 2 ($p=0.051$) (Fig. 4C).

3.4. Shear moduli

No significant differences in shear moduli were found in either G_{31} ($F=2.03$, $p=0.115$) or G_{23} ($F=1.036$, $p=0.405$) among the five dogs. In contrast, G_{12} in dog 1 was consistently different with that in dogs 2, 3, 4, and 5 ($F=5.922$, $p=0.001$). In addition, significant differences in shear moduli G_{12} ($p=0.048$), G_{31} ($p=0.037$), and G_{23} ($p=0.028$) were found between the buccal and lingual anatomical positions in the regenerate cortical bone (Fig. 5A). No significant differences were found in shear moduli between the buccal and lingual anatomical positions in the control cortical bone (Table 2). Furthermore, no significant differences in the regenerate cortical bone between the alveolar and basal relative positions were found in G_{12} or G_{23} (Table 2); however, statistical differences were found in G_{31} ($p=0.035$). In contrast, a significant difference in G_{23} ($p=0.008$) between alveolar and basal positions was the only difference found for the control cortical bone. Complementarily, significant differences in shear moduli G_{12} ($p=0.003$), G_{31} ($p=0.001$), and G_{23} ($p=0.001$) were found between the regenerate cortical bone and the control cortical bone (Table 2), (Fig. 5B). Statistical differences among G_{12} , G_{23} , and G_{31} ($F=63.9$, $p=0.001$) were found (Fig. 5C).

3.5. Poisson's ratio

No statistical differences in Poisson's ratios ν_{13} ($F=2.6$, $p=0.057$) and ν_{23} ($F=2.2$, $p=0.091$) were found among the five dogs. However, a significant difference for ν_{12} ($F=4.3$, $p=0.007$) was found in dog 1 when compared with the same characteristic in dogs 4 and 5 (Fig. 6A). In the same way, no significant differences in Poisson's ratios ν_{12} ($p=0.504$), ν_{23} ($p=0.336$), and ν_{31} ($p=0.611$) were found in the regenerate cortical bone between paired buccal and lingual anatomical positions. However, no significant differences were found between the buccal and lingual sides in the control cortical bone for Poisson's ratio ν_{13} ($p=0.858$) and ν_{23} ($p=0.096$), although a significant difference was reported in ν_{31} .

($p=0.018$) (Table 2). Correspondingly, a test between relative positions in the regenerate cortical bone showed no significant differences in any of the Poisson's ratios ν_{12} ($p=0.193$), ν_{23} ($p=0.052$), and ν_{31} ($p=0.747$). Complementarily, no significant differences in the control cortical bone between relative positions were founded for either ν_{12} ($p=0.123$) or ν_{23} ($p=0.208$); although a significant difference was reported for ν_{31} ($p=0.020$). Finally, no differences in Poisson's ratio for either ν_{12} ($F=1.54$, $p=0.224$), or ν_{23} ($F=1.299$, $p=0.263$) were found between the regenerate and control cortical bone specimens (Fig.6B); although significant differences were found for ν_{13} ($F=6.143$, $p=0.018$). Statistical differences were present among all three principal planes (Fig.6C).

4. Discussion

Discrepancies in sample size between control and regenerate sides were due to failure in obtaining cylindrical regenerate cortical samples from the buccal side because of either the presence of soft tissue inclusions or low cortical thickness. However, the specimen number was statistically representative to allow comparisons among groups.

4.1. Differences among anatomical positions

Although the MBT device is placed in the buccal side, our results showed that the mechanical integrity of the regenerate cortical bone was lower on the buccal than the lingual side of the mandible. This finding could be due to the effect of three factors that can act either independently or jointly: first, the device could produce a stress-shielding effect of the regenerate cortical bone on the buccal side, dampening potential mechanical stimulus; this condition should improve after the device is removed (Kennedy et al., 1989; Laftman et al., 1989). Second, the relative position of the device within the mouth could affect the mechanical quality of the regenerate cortical bone because of its effect on inflammatory processes due to foreign body reaction after device placement (Anderson, 1988). Third, the screws attached to the transport disc on the facial side may affect the quality of the new cortical bone generated by traction on that side.

Differences in elastic mechanical properties between relative positions, alveolar and basal, were present mainly among the control specimens rather than in the regenerate cortical bone. This finding in the control bone could be due to bone adaptations to normal functional patterns of mandibular loading, inertia at the cross section, and the average direction of flexion load, which produces compressive stresses at the basal cortical bone and tensile stresses at the alveolar cortical bone (Alvarez-Arenal et al., 2009). Alternately, lower chewing forces on the regenerate side due to the animal favoring the unoperated side and the stress-shielding effect from the reconstruction plate could also result in overall reduced cortical bone formation in the regenerate.

4.2. Differences between regenerate and control cortical bone

Although very little is known about the biomechanical characteristics of regenerate cortical bone after MBT, it has been assumed that the distracted cortical bone tends to completely restore the mechanical properties, microstructure, and morphological features of the original cortical bone at the end of the mandibular distraction process (Schickendantz et al., 1992). Accordingly, several studies have tried to assess differences between regenerate and control cortical bone after distraction osteogenesis by performing global biomechanical tests that ignore the anisotropic behavior of the cortical bone and consequently assigning a global strength factor to the regenerate cortical bone (Ayoub et al., 2001; Li et al., 2002; Gomez et al., 2005; Kunz et al., 2006). Although, in the present study the elastic mechanical properties of the control cortical bone were higher than the regenerate cortical bone, these differences varied depending on which mechanical property was compared. For instance, density in the

regenerate cortical bone was 88.44 % of the density in the control cortical bone; elastic modulus E_3 in the regenerated cortical bone was 73.57 % of the stiffness in the control cortical bone; and shear modulus G_{12} in the regenerate cortical bone was 77.08% of the control cortical bone.

4.3. Mechanical properties and anisotropy

Although it has been reported that canine mandibular cortical bone is elastically isotropic (Ashman et al., 1985), several studies have reported anisotropic behavior in mammalian mandibles of several species (Ashman et al., 1987; Schwartz-Dabney and Dechow, 2002), and in canine long bones (Ashman et al., 1984). The present study quantified anisotropy using three complementary estimates: first by statistically comparing the three principal elastic moduli, second by comparing relative stiffness between axes by using the ratio E_2/E_3 to measure the relative bone anisotropy in the cortical plane, and third by comparing the directions of maximum stiffness between regenerate and control cortical bone. The principal elastic moduli E_1 and E_2 were statistically different in the control cortical bone ($F=19.1$, $p<0.05$) suggesting an orthotropic organization at a tissue level, whereas they were statistically similar in the regenerate cortical bone ($F=2.5$, $p=0.13$) implying a transversal isotropic organization (Table 3). The relative bone anisotropy in the cortical bone E_2/E_3 was calculated as 0.52 ± 0.12 and 0.50 ± 0.06 for the regenerate and control cortical bone respectively, demonstrating similar differences in these orientations. Lastly, the direction of maximum stiffness in the regenerate and the control cortical bone was found to have the same principal orientation with respect to the lower border of the mandibular corpus. Overall, the calculated values for the principal elastic moduli of the control and regenerate cortical bone were numerically different in all directions, but the control cortical bone showed orthotropic characteristics, while the regenerate cortical bone showed transversely isotropic characteristics because of the similarity between elastic moduli E_1 and E_2 .

4.4. Relationship between density and mechanical properties

The mechanical properties of cortical bone are affected by the density, grade of mineralization, and matrix organization (Rho et al., 1998). In general, bone density increases with time as a result of both remodeling and mineralization, which results in an increase in the strength and stiffness of the cortical regenerate bone (Walsh et al., 1994). Increases in bone density are an important part of the bone healing process following MBT (Harp et al., 1994; Kunz et al., 2006). Density is lower in the regenerate cortical bone at the end of the consolidation time than the control cortical bone (Kunz et al., 2006). Our results showed that average density was about 11% lower in the regenerate cortical bone than the control cortical bone after twelve weeks of consolidation period, which has density values similar to those reported previously for human mandibular cortical bone (Schwartz-Dabney and Dechow, 2003).

Although elastic moduli were deduced using material density characteristics, different relationship patterns were presented between control and regenerated specimens. In the control cortical bone, the trends for the minimum, middle, and maximum elastic moduli when compared with bone density are parallel (Fig. 7B). As the bone density increases, so do the values for E_1 , E_2 , and E_3 . In addition, E_1 and E_2 have similar tendencies, supporting their orthotropic characteristics. These results have the same tendency as the relationship reported by Schaffler and Burr in 1988 (Schaffler and Burr, 1988). They reported a positive correlation between elastic moduli obtained from tension tests and density in bovine cortical bone samples, though density was calculated from measured porosity instead of being measured directly. On the contrary, for the regenerate cortical bone, although the values for E_1 and E_2 are close, their tendencies are convergent (Fig. 7A). This geometrical characteristic seems to suggest an immature tissue representation. In addition, it is possible

to observe two groups of data for every tendency line that may correspond to the previous described difference in density between anatomical positions.

5. Conclusions

As far as it is possible to determine, this is the first report to measure the elastic constants of cortical bone regenerate after MBT osteogenesis by using the non-destructive ultrasonic technique. The results suggest that the control mandibular cortical bone is a transverse isotropic material, whereas the regenerate cortical bone is transversally isotropic with structural elements that tend to be oriented preferentially in the same direction as the distraction process, providing maximum stiffness in that direction. Although there are statistical differences in elastic moduli between regenerate and control cortical bone, both tissues remain anisotropic, and the numerical differences must be due to different grades of mineralization.

Futures studies relating to the biomechanics of the regenerate tissues after the MBT process must consider correspondingly the biomechanical differences in the trabecular bone, the relationship between microstructure and bony mechanical properties, patterns of blood supply in the regenerate tissues and their relationship with mechanical properties, and the effect of growth factors on the microstructure and mechanical properties of the new regenerate tissues.

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Figure 1. Radiographic image from a reconstructed dog's mandible. The MBT device is positioned on the buccal side, with the reconstruction plate (arrowheads) spanning the new bone gap (asterisks) present after transport, and the transport unit (arrow) attached to the bone disk at the anterior border of the gap.

Figure 2.

Box plot of cortical bone density in kg/m^3 . A) between paired regenerate and control specimens in the two anatomical positions. B) Between paired regenerate and control specimens in two relative positions within the mandible. C) Between regenerate and control cortical bone irrespective of position.

Figure 3. Principal stiffness direction distribution through the cortical samples is represented by Rose diagrams. A) Principal direction of maximum stiffness on the buccal and lingual sides. B) Principal direction of maximum stiffness through the 35 cortical specimens.

Figure 4. Box plot of elastic moduli in GPa. A) Between anatomical positions in the regenerate cortical bone. B) Between regenerate and control cortical bone specimens. C) Averaged through the 35 cylindrical cortical bone specimens.

Figure 5. Box plot of shear moduli in GPa. A) Between anatomical positions in the regenerate cortical bone specimens. B) Between regenerate and control cortical bone specimens. C) Averaged among 35 cortical bone specimens.

Figure 6. Box plot of Poisson's ratios. A) v_{12} among subjects. B) Between regenerate and control cortical bone specimens. C) Through 35 cylindrical cortical bone specimens,

Figure 7. Scatterplot of density in kg/m³ and principal elastic moduli in MPa A) at the regenerate cortical bone, and B) at the control cortical bone.

Regenerate and control cylindrical cortical bone specimens. Distribution among subjects, relative positions (alveolar, medial, and basal), and anatomical positions (buccal and lingual).

Table 1

SUBJECT	POSITION	REGENERATE BONE		CONTROL BONE	
		BUCCAL	LINGUAL	BUCCAL	LINGUAL
Dog 1	ALVEOLAR	-	X	X	X
	MEDIA	-	-	X	X
	BASAL	-	X	X	X
Dog 2	ALVEOLAR	X	X	X	X
	MEDIA	-	-	-	-
	BASAL	X	X	X	X
Dog 3	ALVEOLAR	-	-	X	-
	MEDIA	-	X	-	-
	BASAL	-	-	X	X
Dog 4	ALVEOLAR	X	X	X	X
	MEDIA	-	-	-	-
	BASAL	X	X	X	X
Dog 5	ALVEOLAR	X	X	X	X
	MEDIA	-	-	-	-
	BASAL	-	X	X	X
SUBTOTAL		5	9	11	10

Elastic mechanical properties of the canine cortical bone determined by ultrasound wave technique for regenerate and control cortical bone for two anatomical positions (buccal and lingual) and two relative position on the mandible (alveolar and basal).

Table 2

Cortical bone	Specimen position	Density (δ) [mg/cm ³]	E ₁ [GPa]	E ₂ [GPa]	E ₃ [GPa]	G ₁₂ [GPa]	G ₃₁ [GPa]	G ₂₃ [GPa]	ν_{12}	ν_{13}	ν_{23}
Regenerate	Buccal	1557.7±56.5	7.8±0.9	8.7±1.0	17.2±4.6	2.9±0.5	4.4±0.9	5.5±1.3	0.47±0.12	0.23±0.11	0.06±0.09
	Lingual	1861.1±142.0	10.7±1.9	13.1±2.1	27.5±6.5	4.0±0.7	6.2±1.4	7.9±1.5	0.45±0.06	0.18±0.06	0.08±0.03
Control	Buccal	1986.2±42.7	12.6±2.0	15.7±2.3	31.8±2.7	4.8±0.9	7.1±1.0	9.4±1.2	0.43±0.05	0.17±0.04	0.09±0.04
	Lingual	1971.6±119.0	12.7±2.5	15.7±2.7	31.3±3.7	4.8±1.0	7.4±1.2	9.2±1.4	0.42±0.06	0.15±0.02	0.12±0.03
Regenerate	Alveolar	1736.8±189.5	9.5±2.2	12.2±3.6	21.3±5.7	3.8±1.0	5.1±1.2	7.0±1.6	0.40±0.11	0.24±0.06	0.08±0.09
	Basal	1819.8±168.5	11.2±2.6	12.7±3.5	26.5±7.9	4.0±1.1	6.3±1.5	7.6±1.9	0.47±0.05	0.19±0.07	0.09±0.07
Control	Alveolar	1921.9±104.9	11.6±1.0	14.4±0.7	29.2±2.5	4.4±0.3	6.6±0.7	8.2±0.7	0.41±0.05	0.15±0.02	0.13±0.03
	Basal	2023.7±41.9	13.0±2.5	16.2±2.7	33.2±2.6	4.9±1.0	7.6±1.3	9.9±1.0	0.44±0.05	0.17±0.04	0.08±0.03

Canine elastic mechanical properties for both regenerate and control cortical bone compared with averaged mechanical properties reported previously.

Table. 3

Mechanical property	Regenerate cortical bone	Control cortical bone	Canine femur ^a	Canine mandible ^b	Human mandible ^c	Human mandible ^d
E ₁ [GPa]	9.9±2.7	12.6±2.2	12.8	7.39	10.8	12.7
E ₂ [GPa]	11.7±3.6	15.7±2.4	15.6	7.39	13.3	17.9
E ₃ [GPa]	23.1±6.9	31.4±3.1	20.1	7.39	19.4	22.8
G ₁₂ [GPa]	3.7±1.1	4.8±0.9	4.68	2.63	3.81	5.0
G ₃₁ [GPa]	5.6±1.4	7.2±1.1	5.68	2.63	4.12	5.5
G ₂₃ [GPa]	7.0±1.7	9.2±1.3	6.67	2.63	4.63	7.4
ν ₁₂	0.45±0.09	0.42±0.05	0.282	0.403	0.309	0.18
ν ₁₃	0.20±0.07	0.16±0.03	0.289	0.403	0.249	0.31
ν ₂₃	0.08±0.08	0.10±0.04	0.265	0.403	0.224	0.28

^a Ashman et al., 1984
^b Ashman et al., 1985
^c Ashman and Van Buskirk, 1987
^d Schwartz-Dabney and Dechow, 2003