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A micromechanical elastic property study of trabecular bone in the human mandible

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Abstract Micromechanical properties of human mandibular trabecular bone, with particular interest to any site differences were investigated. A mandible was harvested from a 66 year-old female cadaver free from bone disease. It was embedded in PMMA, cut into 2mm sections and polished. Micromechanical property measurements were obtained using the UH3 Scanning Acoustic Microscope (SAM) (Olympus Co., Tokyo, Japan) at 400MHz in the burst mode. 6 vertical slices from the right and 6 horizontal slices from the left were chosen. In each of the 12 samples, 3 points were measured; first in the center, the other 2 from the margins. Data were analyzed statistically by SPSS (SPSS, Inc.) using Student's t-test. The average value of reflection coefficient r is 0.58 ± 0.079 with the range from 0.46 to 0.64; $E = 25.0 \pm 5.64$ GPa. There is no significant difference in properties in the osteonal direction of related cortical bone and those found between the marginal area and center areas. The average value of r from the right side, 0.60 ± 0.07, is statistically higher than the average value of from the left side, 0.56 ± 0.07. Micromechanical properties of both mandibular trabecular and cortical bone have almost the same values.

Introduction

The mandible is not a static piece of bone, but is a dynamic unit that is influenced by forces of mastication from the teeth or prostheses as well as by the forces from the muscles of mastication during chewing. The stresses and strains on the mandible by these various forces result in orientation of the osteons within the cortical regions of the mandible in a unique relationship different from any of the body's long bones.

Many histological and biological studies have been reported on bone, but few have described the mandible. The various muscular and compressive forces on the mandible are unique compared to the long bones. Thus, a clear understanding of the unique mandibular osseous structure/properties relationships is critical when dealing with such concerns as: implant design and treatment planning, mandibular reconstruction techniques, and treatment of fractures, temporomandibular joint dysfunction and various dentoalveolar conditions.

We have previously reported on the relationships between osteonal direction and the micromechanical elastic properties of cortical bone of the human mandible [1]. Scanning acoustic microscopy (SAM) revealed that the osteonal structure in the anterior mandible has the pattern of transverse isotropy parallel to the surface of the mandible. The buccal and inferior surface of the anterior mandible body, as well as the buccal surface within the posterior mandibular body were found to be transversely isotropic in the anterior-posterior direction.

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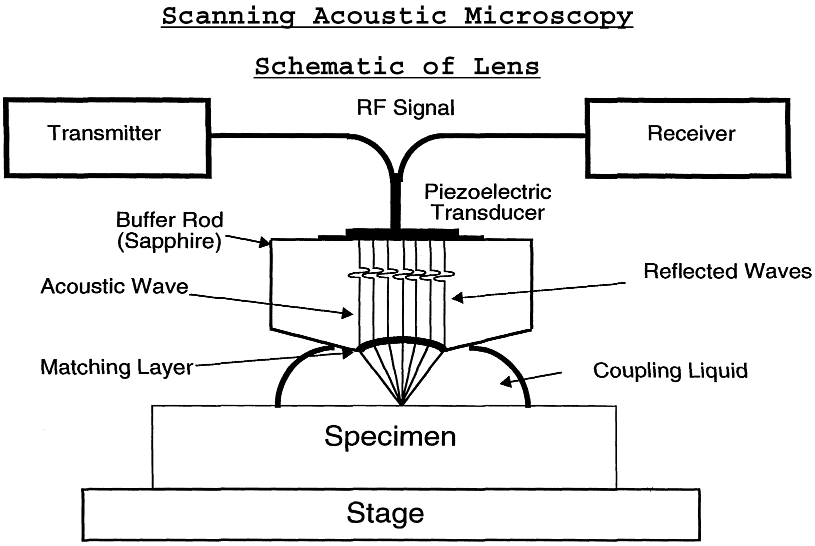

Fig. 1 Diagram of the lens configuration for the UH3 Scanning Acoustic Microscope (Olympus Co., Tokyo, Japan) (Reprinted from DENTAL MATERIALS, 19(3), T.Nomura, E.Gold, M.P.Powers, S.Shingaki and J.L.Katz, Micromechanics/structure relationships in the human mandible, 167–173, (2003), with permission from the Academy of Dental Materials)

There are only a few reports on the micromechanical properties of trabecular bone of human long bones [2–6], and only one on the macromechanical properties for the mandible [7]. The present study was initiated to investigate the micromechanical elastic properties of trabecular bone in the human mandible at high resolution, with particular interest in any site differences.

Materials and methods

An edentulous (teeth were removed pre-mortem) mandible from a 66 year-old female cadaver free of bony disease was obtained. This mandible had been immersed in 10% aldehyde formalin before receiving it for this study. The coordinates system x,y,z are defined **such** that the inferior border of mandibular is positioned on the x-y plane. X is always along the anterior-posterior direction, y is always in the horizontal direction and z is always in superior-inferior direction perpendicular to the x-y plane. The specimen was then reimmersed in formalin prior to analysis. The mandible was cut into 2cm blocks and embedded in polymethylmethacrylate (PMMA, Spurr's Low Viscosity Kit, Electron Microscopy Sciences, PA, USA) as described in our previous report [1]. Finally, each slice was polished by successive sandpapers and subsequently with 0.3 and 0.05 μm aluminum powders. Histological study was done by transmitted light microscopy.

Analysis of the micromechanical elastic properties are done with the UH3 Scanning Acoustic Microscope (Olympus Co., Tokyo, Japan) in the burst mode for high resolution. The SAM block diagram is shown in Fig.1. Studies have been performed at 400 MHz (120ÅK aperture angle, nominal lateral resolution 2.5 μm) over areas from 250 μm (x-dimension) by 200 μm (y-dimension) to 2 mm by 1.6 mm in order to obtain both descriptive maps and quantitative data. Each specimen is connected to the acoustic lens by a drop of water which simultaneously keeps the sample wet and provides the acoustic coupling required for the measurements. The lens is focused on the specimen's surface; the interaction at the material – fluid interface depends on the relation between the acoustic impedances of the two media at the interface (acoustic impedance, Z, is the product of acoustic velocity, v, in the specimen and its local density, ρ, i.e. $Z = \rho v$). Analytically, this interaction that is measured is described as the reflection coefficient, r, where: $r = Z_2 - Z_1/Z_2 + Z_1$, and Z_2 and Z_1represent the acoustic impedances of the material and the coupling liquid respectively (Fig. 2). It is the relative values of r that are stored as voltages in the instrument and put out on a screen as shades of gray whose brightness levels are proportional to the material's r values. The resultant image is a 2-D map related to the elastic properties over the materials' surface.

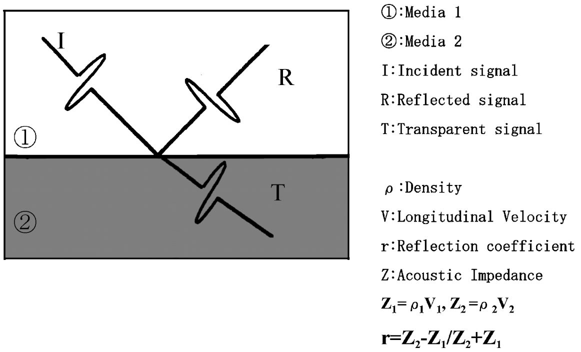

Fig. 2 Sketch of the Incident, I, Reflected, R and Transmitted T wave directions. The reflection coefficient r would be along R. (Reprinted from DENTAL MATERIALS, 19(3), T.Nomura, E.Gold, M.P.Powers, S.Shingaki and J.L.Katz, Micromechanics/structure relationships in the human mandible, 167–173, (2003), with permission from the Academy of Dental Materials)

The number of segments and the orientations in which they were cut and polished allows for mapping the structure of the mandible and its concomitant anisotropic micromechanical elastic properties over the entire surface structure. In order to obtain the actual elastic properties of the appropriate areas in each specimen, a calibration procedure is used. The instrumental voltage value corresponding to a given gray level on the SAM map is compared to a calibration curve obtained by measuring the SAM voltages of materials of known acoustic impedance measured independently. The calibration materials are: titanium (Z = 27.63 Mrayl, r = 0.9), Pyrex glass (Z = 12.58, r = 0.79), polypropylene (Z = 2.48, r = 0.25), Teflon (Z = 2.97, r = 0.33), and Stainless steel (Z = 46.64, r = 0.94) (Fig. 3). In this study, we obtained the following formulation for our calibration curve. $y = 1.32x + 0.11$; $R^2 = 0.972$, where y represents reflection coefficient r, and x represents the voltage. From Bumrerraj and Katz's study [6], Young's modulus was calculated using the following formulation. $y = 1.5081e^{4.8156x}$,where y represents Young's modulus and x represents reflection coefficient.

For this study, 6 slices in each side of mandible were chosen(Fig. 4). In each of the 12 areas, 3 different points were measured: one is in center; the other 2 were chosen at the margin area of trabecular bone (Fig. 5). Each trabecular area was classified into one of 3 categories

according to the related cortical osteonal orientation directions as described in our previous study [1]:

(1) |: all of the osteons are running perpendicular to the x axis.

(2) \ or /: oblique orientations.

(3) -: all of the osteons are running parallel to the x axis.

All data were analyzed statistically by SPSS(SPSS, Inc.) using Student's t-test.

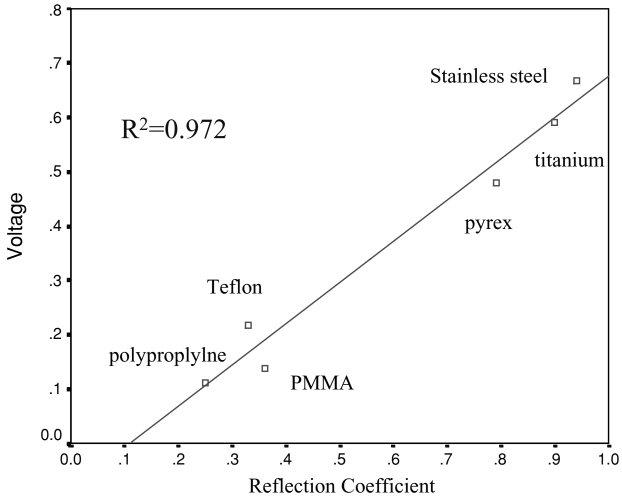

Fig. 3 Calibration curve for reflection coefficient, r, versus SAM voltage based on six standard materials (titanium, pyrex glass, polypropylene, Teflon, PMMA, and stainless steel) (Reprinted from DENTAL MATERIALS, 19(3), T.Nomura, E.Gold, M.P.Powers, S.Shingaki and J.L.Katz, Micromechanics/structure relationships in the human mandible, 167–173, (2003), with permission from the Acadmy of Dental Material.)

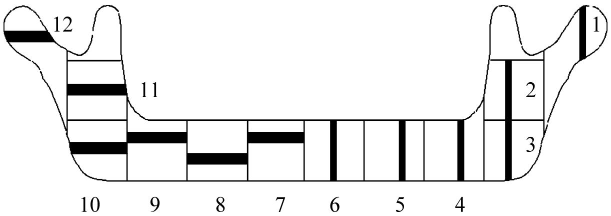

Fig. 4 Sketch of the orientation of the 6 slices in each side of mandible

Results

Mean and SD of the data of the micromechanical elastic properties of mandibular trabecular bone, osteonal orientation of adjacent cortical bone as well as the calculated Young's modulus are given inTable 1. The total mean reflection coefficient, r, value for the data was 0.58 ± 0.079 with range from 0.46 to 0.64. In terms of orientation, there is no difference among the three orientation direction groups(Table 2). In terms of sample location, data from the margin yielded $R = 0.57 \pm 0.10$, while the data from the center yielded $r = 0.59 \pm 0.10$; there is no statistical difference between the two(Table 3). These samples also were analyzed according to the whether they were from the left side or the right side of the mandible. The average of the data taken from the right side yielded $r = 0.60 \pm 0.070$, and is statistically higher than the average of the data taken from the left side, $r = 0.56 \pm 0.070$(Table 4).

Discussion

The mean values of r for the mandibular trabecular bone is 0.58, the mean value of Young's modulus of all samples is 25.0 ± 5.64 GPa. As mentioned in the previous paper, data of the formalin embedded sample is almost 2 times higher than that of fresh sample [1]. If trabecular bone properties are affected in the same manner, although it might be somewhat shielded from as large an increase as that experienced by the readily available cortical bone, then the data would imply that Young's modulus would be of the order of 12 to 15 GPa. The scaled data is comparable to other investigators' human data, e.g. 14.8 GPa (tibia, Rho et al. [2], 13.0 GPa (femur, Ashman and Rho [3], 14.91 GPa (femur, Turner et al. [4], 11.4 GPa (femur, Zysset et al. [5] with Nanoindentaion, 17.4 GPa (fresh femur, Bumrerraj and Katz [6]

There is also a report for mandible from Misch et al. [7]. They reported the elastic property of trabecular bone as 0.056Gpa, based on compressive studies by mechanical measurements on blocks of trabecular bone. It is very clear that big difference between Misch et al. [7] with all the other reports cited above as well as with the data presented here, is that the former were measuring a highly porous, bulk specimen by mechanical testing. It is well known that Young's modulus decreases quite rapidly with increase in porosity. In this case, the large amount of porosity effects the modulus measured in such bulk specimens. Therefore it is unrealistic to assign a value of trabecular modulus from such measurements. Both the SAM study here and the nanoindentation studies measure the properties on the trabecular directly without including the pores.

In terms of site differences, the data were not related to the osteonal direction of the adjacent cortical bone; also, there is no difference between the marginal area and center areas. One of the most interesting observations made in this study is that there is a statistical difference between data from the vertical section (left side) and those from the horizontal section (right side). It is not clear what might be the cause of this difference. One possibility is that it might reflect a mild anisotropy. The distribution and direction of the trabecular bone components are thought to control the properties differently from that found for cortical bone. Further study is needed in this area. Regarding the trabecular structure of the mandible, only one detailed report has been presented, that by Nakajima et al. [8]. In their report, a complicated trabecular bone arrangement was seen.

Table 1 Mean and SD of the elastic mechanical properties of mandibular trabecular bone in terms of sites

Site	r mean	SD	Young's modulus (GPa)	Direction (cortical osteon)
1	0.54	0.05	21.7	/
2	0.64	0.08	33.7	/
3	0.62	0.09	30.9	/
4	0.62	0.10	30.4	/
5	0.55	0.11	21.9	–
6	0.57	0.08	23.8	–
7	0.60	0.06	28.1	|
8	0.57	0.06	22.2	|
9	0.60	0.07	29.5	|
10	0.59	0.08	26.7	/
11	0.46	0.07	14.4	/
12	0.49	0.08	16.3	/
r = 0.58 ± 0.079			E = 25.0 ± 5.64GPa	

Many histological and biological studies have been reported on bone, but few have described the mandible. The various muscular and compressive forces on the mandible are unique compared to the long bones. Thus, a clear

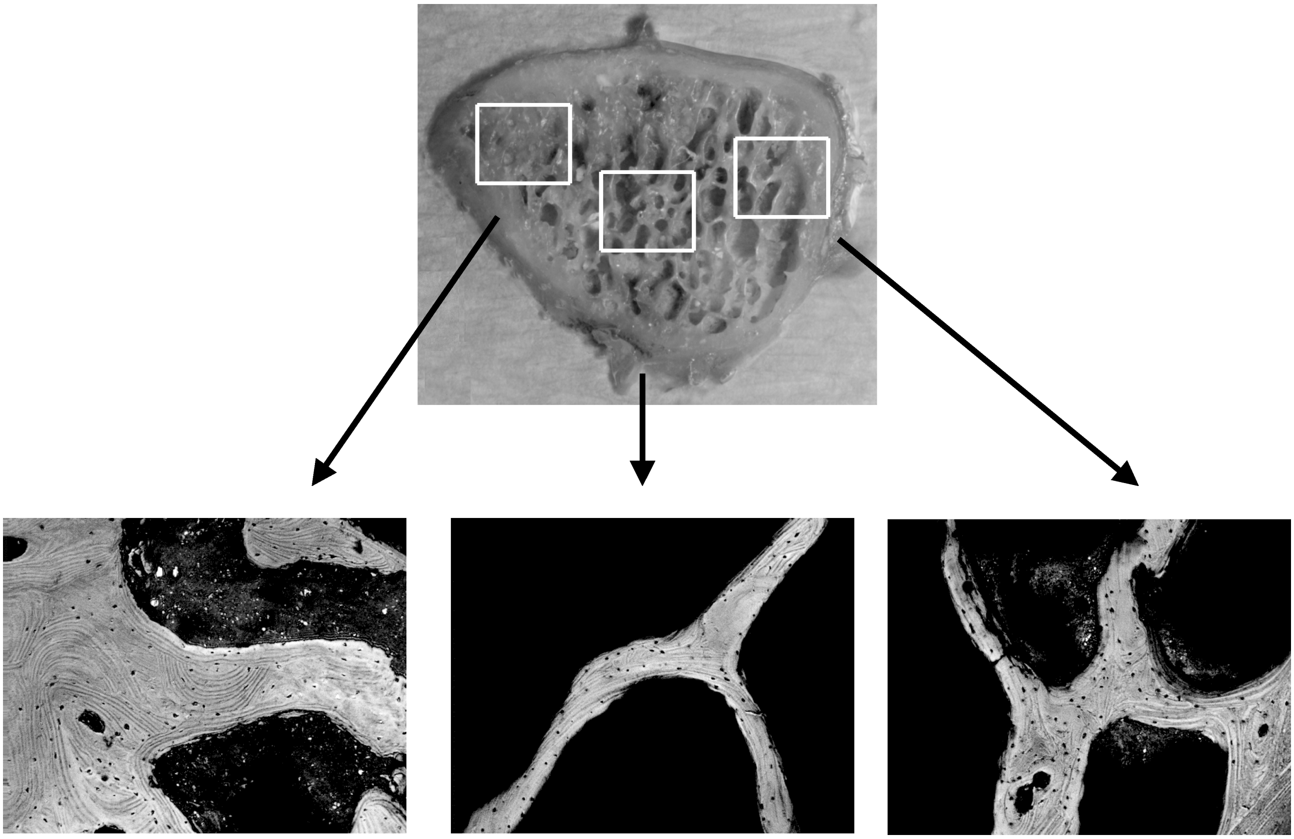

Fig. 5 In each of the 12 areas, 3 different points were measured: one at the center; the other 2 at the margins of the trabeculae

Table 2 Mean and SD of the elastic mechanical properties of mandibular trabecular bone in terms of related osteonal directions

Direction	Mean	SD	Young's modulus (GPa)
–	0.56	0.01	22.9
/	0.57	0.02	23.8
|	0.56	0.03	22.9

Table 3 Mean and SD of the elastic mechanical properties of mandibular trabecular bone in terms of sample location

Location	Mean	SD	Young's modulus (GPa)
Marginal	0.57	0.10	23.7
Center	0.59	0.10	25.3

Table 4 Mean and SD of the elastic mechanical properties of mandibular trabecular bone in terms of side from which samples were taken

Side	Mean	SD	Young's modulus (GPa)
Right	0.60	0.07	26.6
Left	0.56	0.09	22.1
			$p < 0.001$

understanding of the unique mandibular osseous structure/properties relationships is critical when dealing with such concerns as: implant design and treatment planning, mandibular reconstruction techniques, and treatment of fractures, temporo-mandibular joint dysfunction and various dentoalveolar conditions. As this study was done in only one mandible, the variation in terms of age, gender and dental status was not evaluated. However, we can correlate the mechanical properties of the mandibular trabecular bone with the directions of the osteons in the cortical regions in the same bone, as we have used the same mandible as in our previous study of cortical bone micromechanics [1].

Conclusion

The total mean value of r for the data of mandibular trabecular bone was 0.58 ± 0.079 with a range from 0.46 to 0.64; the mean value of Young's modulus, $E = 25.0 \pm 5.64$ GPa with a range from 14.4 to 33.7 GPa. There is no difference in trabecular properties associated with the neighboring osteonal directions of the cortical bone sites. The only statistically significant difference was found between data from the vertical section (left side) and the horizontal section (right side).

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