Three-dimensional morphometric analysis of the trabecular bone in the human mandible using microcomputed tomography

Hong Seok Moon

The Graduate School
Yonsei University
Department of Dental Science

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This certifies that the dissertation of Hongseok Moon is approved

Thesis supervisor : Moon-Kyu Chung

Ho-Yong Lee

Dong-Hoo Han

Chong-Hyun Han

Kee_Deog Kim

The Graduate School

Yonsei University

December 2001

감사의 글

이 논문이 완성되기까지 많은 분들의 도움이 있으셨습니다. 세심한 배려와 인내심으로 부족한 논문을 이끌어 주신 정문규 지도교수님께 우선 감사 드립니다. 이호용 교수님의 학문적, 인격적깊이는 선생님께 배운 가장 소중한 가치였습니다. 또한 한동후, 한종현, 김기덕 교수님의 논문에 대한 통찰력과 날카로운 지적은 논문을 더욱 충실하게 만들었습니다. 동경대 치과대학 해부학교실의 Ide 교수님은 저에게 Micro-CT 를 처음으로 접할 수 있는 귀한 기회를 주셨으며 이순기 선배님의 도움이 없었다면 동경치대방문이 어려움 없이 이루어질 수 없었을 것입니다. 시편채득을 위하여 많은 도움을 주신 해부학교실의 김희진 교수님과 논문계획서에 대하여 논문가치와 중요성에 대한 공감을 가지고 용기를 주신 Columbia 대학의 Peter Wang 교수님, 한국에서 처음으로 Micro-CT 를 이용할 수 있도록 도와주신 진단방사선학교실의 김희중 교수님과 정해조 박사님, 다른 분야임에도 불구하고 진지한 토론과 아낌없는 충고와 지원을 해주신 아주대학교 정형외과학교실의 원예연 교수님과 어려운 여건 속에서도 저의 실험을 위하여 시간과 노력을 아끼지 않으신 손기욱 , 백명현 연구원, 논문의 이론적 깊이를 더할 수 있도록 해준 Skyscan 사의 Erik Buelens, 통계처리를 도와준 박란 선생과 논문의 완성도를 높일 수 있도록 도와준 이철영, 이상화, 박재한선생, 시간이 모자란 가운데서도 졸속한 문장을 훌륭하게 처리해준 배은경, 지성훈 선생에게 무한한 감사의 뜻을 전합니다. 보철학교실의 이근우, 심준성 교수님의 지속적인 관심과 배려에도 감사를 드립니다.

마지막으로 어떠한 상황에서도 저의 버팀목이 되어주신 양가 부모님과 가족들에게 절절한 감사의 뜻을 전합니다. 기쁠 때보다는 어려울 때 힘이 되어 주신 분들입니다. 논문을 쓰는 남편과 항상 함께하고 논문막바지에 매너리즘에 빠진 제게 자극을 주며 용기를 북돋아준 나의 아내에게 한없는 애정과 고마움을 느끼며 이 논문을 바칩니다.

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ABSTRACT

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The mandible has unique functional and structural characteristics when compared with other skeletal bones of the body. Especially the presence of dentition is considered as the most characteristic features of the mandible. Through the dentition, any external forces such as occlusal force can be transmitted to the bone and effect on the bone mass and structure.

There have been numerous studies of the bone structure in the other parts of the body and emphasized on its importance. On the mandible, there have been studies on bone mass and density regarding alveolar bone resorption, tooth loss and implant success rate, however little has been studies on the bone structure.

The purpose of this study is to analyze any correlation between trabecular bone structure of the mandible and masticatory function, and the efficacy of micro-CT in biomechanical analysis in dentistry. Skyscan 1072 (SKYSCAN, Antwerpen, Belgium) was used in scanning alveolar and basal bone of premolar and molar regions of the mandible and following results were obtained.

1. In intrasite comparison, the alveolar bone had higher values of bone volume fraction and trabecular number but lower in trabecular separation than the basal trabecular bone. A compacted with a large portion of trabecular bone in alveolar bone could be concluded.
2. When the basal bones superior and inferior to mandibular canal were compared, bone volume fraction and trabecular number at superior region had higher values that were statistically significant. Trabecular separation and degree of anisotropy on the other hand were low, which implies that the basal bone in superior region were more compact in

structure.

3. When the same site of molar and premolar regions were compared, a higher bone volume fraction and trabecular number were found in molar alveolar region which implies a compact structure. Trabecular separation, degree of anisotropy and structural model index in molar regions had lower values and it could be concluded that this area had trabecular bone which has more plate-like structure and less polarity of trabecular bone than premolar region, indicating adequately remodeling zone against the external forces.
4. In basal bone, all parameters between premolar and molar regions were statistically not significant.
5. In the relationships between bone volume fraction and other parameters, a linear correlation was found with other parameters and some relationships appear strong such as trabecular separation, trabecular number and structure model index.

In reference to the results above, it can be concluded that the structure of mandible is appropriately designed to perform and withstand occlusal forces and masticatory function. It is more clearly noted in the molar regions and these facts should be considered in biomechanical analysis of the mandible.

Key word : Micro-CT, mandible, bone structure, trabecular bone

Three-dimensional morphometric analysis of the trabecular bone in the human mandible using microcomputed tomography

Department of Dental Science,
Graduate School, Yonsei University
(Directed by Prof. Moon-Kyu Chung, D.D.S., PhD.)

Hong-Seok Moon

I . INTRODUCTION

The mandible has unique functional and structural characteristics comparing with other skeletal bones of the body; U-shape structure that rotates and translates guided by the condyle and glenoid fossa of the temporal bone and performs a complex functions such as chewing, speech and swallowing.

The trabecular bone of mandible can be divided into alveolar and basal bone[1]. Any pressure from dentition during the function is directly transmitted to trabecular bone. In addition, alveolar bone continues to remodel and change throughout the life in response to tooth movement, loss of dentition, or masticatory characteristics[2, 3]. Therefore, the trabecular bone mass, structure and anisotropic property will vary depending on the alveolar and basal bone with dentition in position. Even within the anterior and posterior area of the mandible might also have different magnitude or direction of forces and bony structure in response to these variations.

Periodontal diseases and its treatment, and the result of prosthetic treatments including osseointegrated dental implants may affect and related to bone mineral density (BMD), trabecular bone structure, and degree, magnification or frequency of occlusal force. However, there have been few studies on mandibular bone structure. As a result, this has not been considered as an important factor during dental treatment and only been analyzed subjectively if at all.

Aging process and diseases, which affect the bony changes such as osteoporosis, continues deterioration or alteration in bone qualities and structures.[4, 5] The effects of these are reflected on the mechanical properties of bone such as decreased fracture resistance from external pressure[6-10], reduced resistance in bone resorption[11-18], decreased support for normal occlusal force or tooth loss[19], impaired success rate of implant[20] and periodontal treatment.[21-25] The most studies, however, have focused on bone mass as the most important predictor in investigating the cause of disease and understanding the trabecular bone and its structure, including the biomechanical competence of trabecular bone[5]. The large variations observed in the biomechanical aspect of trabecular bone cannot be explained unless structural properties are included in the analysis.[26-29] As an example, 94% of mechanical properties of trabecular bone could be explained in using combination of bone density and architectural measurement but 64% with bone density measurement alone[30]. Therefore, more consideration should be given in measuring the trabecular microstructure in addition to bone mass measurements. It is common to analyze both bone quality and trabecular bone structure when studying osteoporotic fracture of femur and lumbar vertebrae[5].

Quantitative bone morphometry is a method to assess structural properties of trabecular bone[5]. The trabecular bone has plates, rods and combination of these in their microstructure[31]. For the analysis of complex trabecular structure, three-dimensional data sets are required to reconstruct and visualize the trabecular bone in three-dimensional image. This overcomes the limitation of traditionally used two-dimensional analysis which one must be assumed that one single image from histologic sectioning was a representative of entire specimen. And one can clearly observe the plate-like structure of trabecular bone that cannot be detected in a two-dimensional image.

The serial-sectioning technique[32] is the classic way of generating three-dimensional data set, but this conventional approach to morphologic measurements typically entails substantial preparation of the specimen, including embedding in methylmethacrylate, followed by sectioning into slices. Although it offers high spatial resolution and image contrast, it is not an easy work and time-consuming technique. Destruction of specimen also prevents further measurements in mechanical analysis of different planes.[33, 34] The mechanical analysis of different planes is very desirable due to the anisotropic nature of the bone.

Micro-computed tomography(micro-CT) is an alternate approach to image and quantify trabecular bone in three dimensions. The field was pioneered by Feldkamp et al,[28] who used an X-ray based micro-tomographic system to create a three-dimensional object with a typical resolution of 50 ㎛.

It is highly accurate, non-destructive method that enables to produce a three-dimensional image with two-dimensional array of detector, where a larger number of slices and immediate analysis of small-sized calcified specimens is achievable[34, 35]. Another widely used in laboratory investigation is a scanner developed by Rüeggsegger et al. with spatial resolution of 15-20μm.[36]

The morphometric analysis of bone biopsies using micro-CT had high correlations to the results obtained with the conventional histologic section as a gold standard.[33, 37]

A common but frustrating and limiting method to assess mandibular bone quality and structure is through periapical radiography. Although computed tomography can be used in assessing cortex and trabecular bone separately with a consistent imaging, it is insufficient to measure accurate bone structure and its changes. As it is uncertain whether the mandible correlates with changes in the rest of skeletal bone, the latter is not suitable for inferring the trabecular bone structure of the mandible.[38-43]

Therefore, the purposes of this study are 1) to measure the trabecular microstructure of alveolar and basal bone of premolar and molar region in the mandible using micro-CT and compared among them for any differences, 2) to analyze trabecular bone values of different sites for any correlation with masticatory function, and 3) to provide fundamental basis for more accurate biomechanical analysis such as micro-finite element analysis of the mandible.

II . MATERIALS AND METHODS

A . Sample preparation

Thirty same-sided premolar and molar regions of the mandible were sectioned from 15-cadaver using a diamond saw(Maruto, model 89-040591, Japan) for the analysis. A severely absorbed mandible, dentition with apical lesions or any pathosis detected in the trabecular bone using periapical radiography were excluded in this study.

To measure the interproximal area of premolar and molar region, the adjacent teeth were longitudinally sectioned. Each specimen had a diameter of no more than 21mm, small enough for the specimen to be in the field of view(FOV) during CT scanning.

The specimens were fixated with 10% buffered formalin solution and dehydrated in 70% alcohol solution.

B . Micro CT imaging

The specimen was scanned and reconstructed into the three-dimensional structure with microcomputed tomography(Skyscan 1072, SKYSCAN, Antwerpen, Belgium). It consists of an x-ray shadow microscopic system which has a high definition x-ray microfocus tube with a focal spot of 10 μm, a 1.0mm thickness of aluminum filter to remove noise during X-ray scanning, precision controlled specimen holder, two-dimensional x-ray CCD camera connected to the frame-grabber and a dual Pentium III computer with tomographic reconstruction software program (Fig. 1).

The specimen is placed between the X-ray source and the CCD camera as a detector. The transmitted and absorbed x-ray from the specimen is transformed into light by a phosphorous screen which is detected by the two dimensional CCD camera. Then, the data is digitalized by the frame-grabber and transmitted to a computer with tomographic reconstruction software. While the specimen placed on the holder, staying in the field of view, it is rotated around the vertical axis at 0.9 degree for 180 degree, producing 200 projections. The projection images are reconstructed into three-dimensional image using the software program(CT-Analyzer™, Ant™, Skyscan, Belgium). It takes over six hours to obtain the integrated image of an specimen at each 200 positions and to reconstruct and analyze the resulting three-dimensional image.

C . Stereological analysis

Both alveolar interproximal bone and basal bone between first and second premolar and between second premolar and first molar teeth in the mandible were measured for the trabecular structural analysis. The alveolar bone measurements were taken at the adjacent areas of periodontium above the level of root apices but 2.5 mm below the alveolar crest to prevent any effect of periodontal diseases present. At the basal bone, two measurements were taken from superior and inferior to the mandibular canal. The region of interest was chosen 1.0 mm away from the mandibular canal. The imaging was taken at least 100 μm from the sectioned surface of the specimen to minimize any influences to the microstructure of the sample from sectioning.

The specimen was placed on a specimen holder, which is 14 mm in diameter for imaging. The cross-sectional images were created with 1024 x 1024 pixels. Each pixel size was 21.3 x 21.3 μm^2 and distance between each cross-sectional images was 21.3μm. From the two-dimensional images, a three-dimensional structural images with voxels in size of 21.3 x 21.3 x 21.3 μm^3 were created.

After scanning the specimen, volume of interest (VOI) of four regions from the three-dimensional reconstruction images were measured (Fig. 2). Two alveolar bone measurements of 100 x 100 x 100 voxels(2.13 x 2.13 x 2.13 mm^3) were taken from the upper and lower portion of alveolar bone. The basal bone measurements of 200 x 200 x 200 voxels(4.26 x 4.26 x 4.26 mm^3) were taken from superior and inferior to the mandibular canal. The gray value images were segmented with an aluminum filter of 1.0mm in thickness to remove noise and a fixed threshold of 200 to extract the mineralized bone from the non-bone area.

From these images, the structural parameters were assessed using direct assessment techniques.

1. Primary parameters

Bone surface area (BS) is calculated by the Marching Cubes method to triangulate the surface of the trabecular bone.[44]

Bone volume (BV) is calculated using polyhedrons corresponding to the enclosed volume of the triangulated surface.[45]

Total volume (TV) is the volume of the whole examined sample and the normalized index, bone volume fraction (BV/TV) enables the comparison of samples of different size. The specific bone surface-to-volume ratio is given by bone surface density (BS/BV).

2. Directly assessed parameters

Measuring the actual distances in the three-dimensional space allows direct assessments of metric indices. Therefore, the values obtained were not from an assumed model or biased by deviations of the actual structure.

The mean thickness of the trabeculae, trabecular thickness (Tb.Th), is obtained by filling maximum size of spheres in the structure with the distance transformation.[46] Then the average thickness of all bone voxels is calculated to give Tb.Th.

Trabecular separation(Tb.Sp) is the mean thickness of the marrow cavity. This value is calculated by using same method as the Tb.Th but the spheres are filled into non-bony part. Tb.Sp is thus the thickness of the marrow cavities.

Trabecular number(Tb.N) is defined as the number of trabecular bone per unit length and taken as the inverse of the mean distance between the midaxes of the structure. The midaxes of the structure are assessed from the binary three-dimensional image with the three-dimensional distance transformation and extracting the center points of nonredundant spheres which filled the structure completely. Then the mean distance between the midaxes is determined in analogy to the Tb.Sp calculation, i.e., the separation between the midaxes is assessed.

3. Directly assessed nonmetric parameters

Structural Model Index(SMI), an estimation of the plate-rod like characteristic of the structure[47] is calculated by a differential analysis of a triangulated surface of the structure and is defined as

$$SMI=6\{(BV(dBS/dr))/BS^2\}$$

dBS/dr is the surface area derivative with respect to a linear measure r, corresponding to the half thickness or the radius assumed constant over the entire structure

The SMI values of 0 and 3 are an ideal plate and rod values, respectively. If both the rod and plate thickness are existed in a structure, the SMI values can vary between 0 to 3.

The degree of anisotropy (DA) represents the structural orientation and the definition is the ratio between the maximal and the minimal radius of the MIL ellipsoid[48-50]**.** By superimposing parallel test lines in different directions on the 3D image, the MIL distribution can be calculated. The directional MIL is the total length of the test line in one direction divided by the number of intersections with the bone-marrow interface of the test lines in the same direction. The MIL ellipsoid is calculated by filling the directional MIL to a directed ellipsoid using a least square fit.

D . Statistical Analysis

Statistical analysis was performed using the SAS V8.1(SAS Institute, Cary, NC). All results were expressed as mean and standard deviation. Paired *t* test was used in comparing differences between basal and alveolar trabecular bone of the mandible and relationship between each specific bone sites of premolar and molar regions. To test for relationships between BV/TV and other parameters, Pearson's correlation analysis was performed. The level of statistical significance was set at $p<0.05$.

III . RESULTS

A . Qualitative analysis

The visual examination of the structural type of specimens shows high interindividual variation and significant differences within the sites of a specimen, especially in the basal trabecular bone inferior to the mandibular canal. In both alveolar and basal bone, a mixed type of both plate-like and rod-like structures could be observed. The alveolar bone had a compact structure whereas the basal bone inferior to the mandibular canal had extensively variable but lower bone mass and more rod-like structures than the other sites. This tendency was more obvious in the molar region than the premolar area. Figure 3 gives an example of typical images. The specimen was premolar region.

B . Quantitative analysis

From tables 1 and 2, no statistical significance could be found in all parametric values between inferior and superior alveolar trabecular bone of both premolar(T_t,T_b) and molar regions(T_T,T_B). Therefore, the two sites were averaged and compared with other regions (Table 3).

Table 1. The parametric values of alveolar trabecular bone in the premolar region(T_i , T_s)

	T_i	T_s	
	Mean (SD)	Mean (SD)	*p* value
Bv/Tv	28.58(15.38)	29.37(13.58)	NS
Bs/Bv	13.54(4.69)	14.44(4.63)	NS
Tb.Th	0.27(0.07)	0.24(0.09)	NS
Tb.Sp	0.62(0.13)	0.58(0.13)	NS
Tb.N	1.18(0.23)	1.26(0.23)	NS
D.A	0.75(0.17)	0.76(0.10)	NS
SMI	1.64(0.57)	1.46(0.48)	NS

$p < .05$

Values are mean and SD. *p* value indicates a significant difference between parameters(p<0.05). T_i : Inferior portion of the alveolar trabecular bone; T_s: Superior portion of the alveolar trabecular bone; BV/TV: Bone volume fraction (%); BS/BV: Bone surface density (mm^2/mm^3); Tb.Th: Trabecular thickness (mm); Tb.Sp: Trabecular separation (mm); Tb.N: Trabecular number (1/mm); DA: Degree of anisotropy; SMI: Structural model index; S: Significance; NS: No significance

Table 2. The parametric values of alveolar trabecular bone in the molar region(T_I, T_S)

	T_I	T_S	
	Mean (SD)	Mean (SD)	*p* value
Bv/Tv	41.03(13.56)	45.55(13.77)	NS
Bs/Bv	13.39(3.09)	12.77(3.26)	NS
Tb.Th	0.27(0.06)	0.29(0.06)	NS
Tb.Sp	0.43(0.08)	0.4(0.08)	NS
Tb.N	1.45(0.19)	1.46(0.13)	NS
D.A	0.64(0.19)	0.62(0.20)	NS
SMI	1.02(0.62)	0.95(0.54)	NS

$p < .05$

T_I : Inferior portion of the alveolar trabecular bone

T_S : Superior portion of the alveolar trabecular bone

Table 3. The averaged parametric values of alveolar trabecular bone in the premolar and molar regions

	T_p			T_m		
	Mean (SD)	Min	Max	Mean (SD)	Min	Max
Bv/Tv	28.98(13.26)	14.50	63.64	43.29(12.63)	28.36	67.99
Bs/Bv	13.99(4.23)	6.78	22.06	13.08(3.03)	8.00	18.00
Tb.Th	0.25(0.08)	0.13	0.44	0.28(0.06)	0.21	0.40
Tb.Sp	0.6(0.09)	0.38	0.72	0.42(0.06)	0.31	0.51
Tb.N	1.22(0.19	0.98	1.61	1.45(0.13)	1.26	1.70
D.A	0.75(0.11)	0.53	0.89	0.63(0.16)	0.39	0.92
SMI	1.55(0.46)	0.47	2.15	0.99(0.55)	0.02	1.64

T_p; Alveolar trabecular bone of premolar region

T_m; Alveolar trabecular bone of molar region

Table 4 and 5 represents the parametric values of basal trabecular bone in the premolar and molar regions.

Table 4. The parametric values of basal trabecular bone superior to the mandibular canal in the premolar and molar regions

	M_p			M_m		
	Mean (SD)	Min	Max	Mean (SD)	Min	Max
Bv/Tv	19.60(11.18)	7.13	51.12	22.03(12.71)	8.66	48.79
Bs/Bv	12.02(3.37)	4.08	18.37	13.32(2.41)	9.67	18.47
Tb.Th	0.29(0.10)	0.12	0.51	0.28(0.03)	0.23	0.33
Tb.Sp	0.92(0.29)	0.50	1.42	0.82(0.31)	0.43	1.55
Tb.N	0.88(0.24)	0.59	1.46	0.96(0.22)	0.55	1.33
D.A	0.79(0.09)	0.57	0.91	0.72(0.16)	0.45	0.90
SMI	1.68(0.52)	0.75	2.75	1.21(0.83)	-0.49	2.38

M_p; Basal trabecular bone superior to the mandibular canal in the premolar region

M_m; Basal trabecular bone superior to the mandibular canal in the molar region

Table 5. The parametric values of basal trabecular bone inferior to the mandibular canal in the premolar and molar regions

	B_p			B_m		
	Mean (SD)	Min	Max	Mean (SD)	Min	Max
Bv/Tv	12.09(7.41)	2.55	24.16	12.37(10.07)	0.24	31.99
Bs/Bv	13.97(4.77)	6.72	22.72	16.08(5.19)	7.11	28.01
Tb.Th	0.24(0.07)	0.12	0.40	0.26(0.08)	0.14	0.47
Tb.Sp.	1.28(0.35)	0.79	2.32	1.17(0.27)	0.86	1.79
Tb.N.	0.70(0.17)	0.40	1.05	0.71(0.10)	0.52	0.87
D.A.	0.86(0.09)	0.59	0.97	0.86(0.08)	0.74	0.99
SMI	1.76(0.38)	1.07	2.43	2.01(0.81)	0.59	3.02

B_p; Basal trabecular bone inferior to the mandibular canal in the premolar region

B_m; Basal trabecular bone inferior to the mandibular canal in the molar region

Bone volume fraction (BV/TV) had a large variation with the range of values from 0.24% to 67.99%. The largest value was at the alveolar trabecular bone in the molar region (T_m) and the lowest one was at the basal bone inferior to the mandibular canal in the molar region (B_m). The mean BV/TV in alveolar bone of molar region (T_m) was the largest and inferior to the mandibular canal in the premolar region (B_p) had the smallest in value**.**

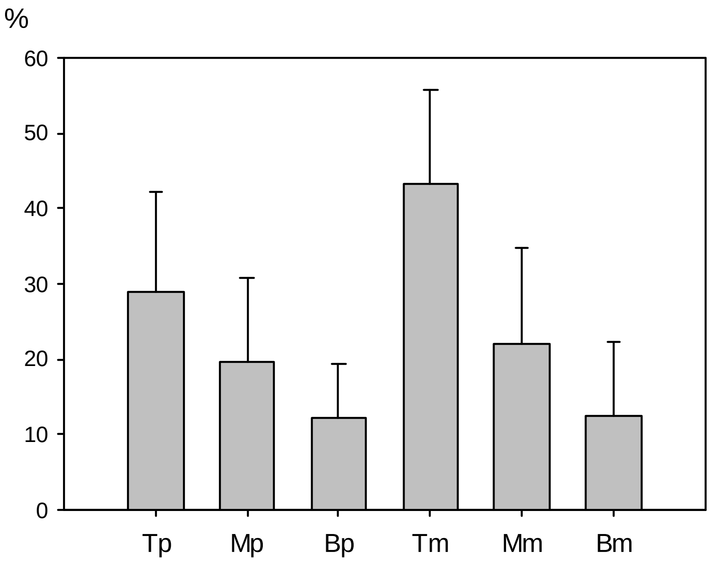

Fig. 4. The comparison of bone volume fraction(BV/TV) in the premolar and molar regions.

T_p; Alveolar trabecular bone in the premolar region

T_m; Alveolar trabecular bone in the molar region

M_p; Basal trabecular bone superior to the mandibular canal in the premolar region

M_m; Basal trabecular bone superior to the mandibular canal in the molar region

B_p; Basal trabecular bone inferior to the mandibular canal in the premolar region

B_m; Basal trabecular bone inferior to the mandibular canal in the molar region

Bone surface density (BS/BV) ranged from 4.08 mm^2/mm^3 to 28.01 mm^2/mm^3. The highest value could be found in the basal bone inferior to the mandibular canal in the molar region and the lowest value in the basal bone superior to the mandibular canal in the premolar region. The mean BS/BV is highest at inferior to the mandibular canal of the basal bone in the molar region and the lowest at superior to the mandibular canal of the basal bone in the premolar region. However, there were minimal variations between the two extreme values.

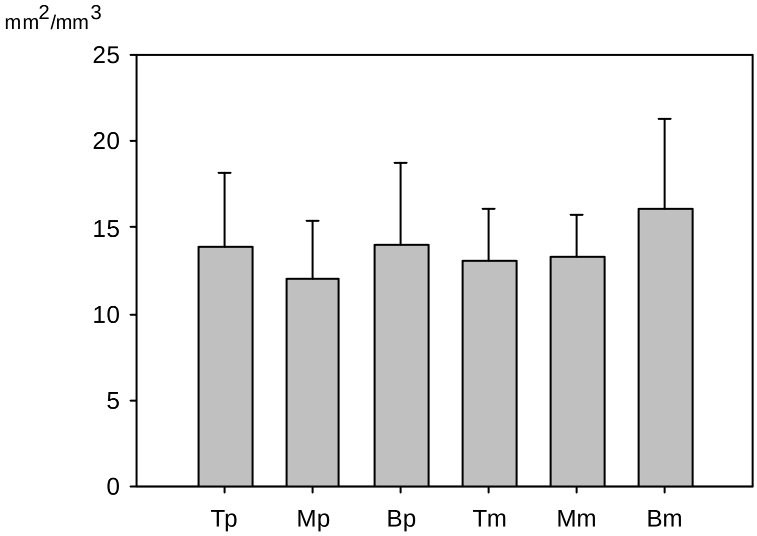

Fig. 5. The comparison of bone surface density (BS/BV) in the premolar and molar regions.

One of the structural parameters, trabecular thickness (Tb.Th) ranged between 0.12 mm to 0.51 mm and the maximum Tb.Th was found in the premolar regions superior to the mandibular canal. In the basal bone of premolar regions (M_p & B_p), all had minimum Tb.Th. Mean Tb.Th was also higher in the premolar region superior to the mandibular canal and the premolar region inferior to the mandibular canal was the lowest but the difference in value was minimal within the limit of 0.24 and 0.29 mm**.**

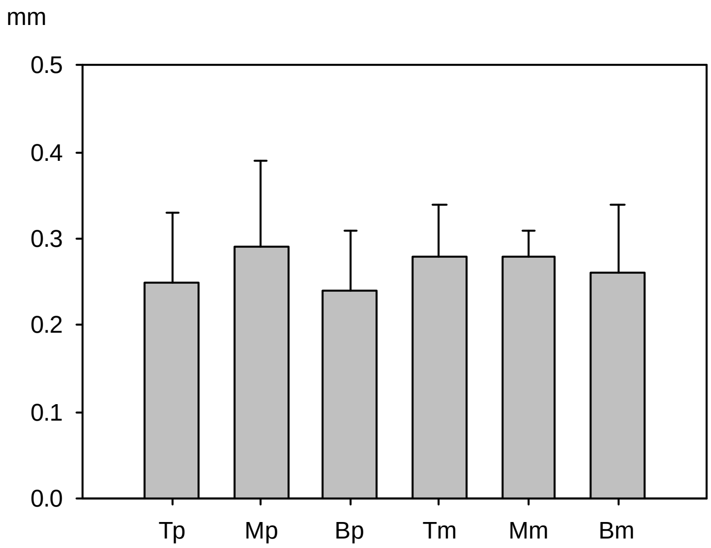

Fig. 6. The comparison of trabecular thickness (Tb.Th) in the premolar and molar regions.

Trabecular separation (Tb.Sp) ranged between 0.31 mm to 2.32 mm. The highest value at the premolar region inferior to the mandibular canal and the lowest at the alveolar bone in the molar region. Mean Tb.Sp values were also followed a similar trend.

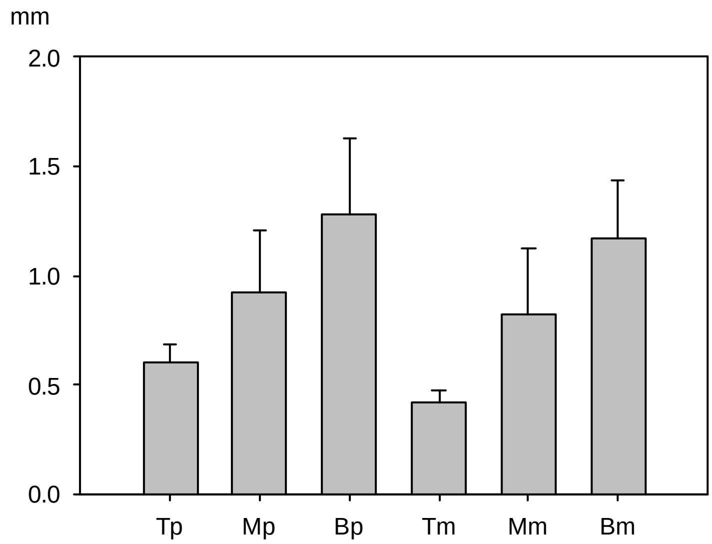

Fig. 7. The comparison of trabecular separation (Tb.Sp) in the premolar and molar regions.

Trabecular number (Tb.N) was between 0.40 and 1.70. Tb.N and mean Tb.N was lowest at the premolar region inferior to the mandibular canal and had minimal differences with that of the molar region. The highest mean Tb.N and maximum number were measured at the alveolar bone in the molar region.

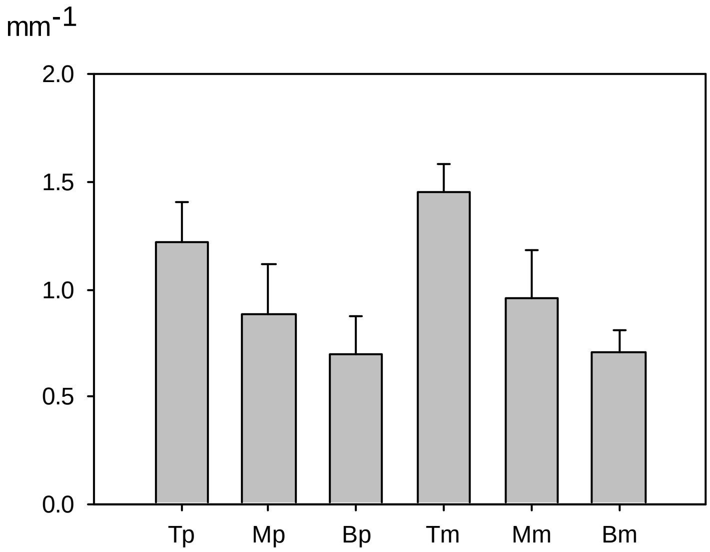

Fig. 8. The comparison of trabecular number (Tb.N) in the premolar and molar regions.

Trabecular bone polarity was shown as a degree of anisotropy (DA) and the values lied between 0.39 and 0.99. The maximum DA value was found at the molar region inferior to the mandibular canal and both premolar and molar regions inferior to the mandibular canal had the highest mean DA, which indicates high-polarized condition along the common axis. The molar region of the alveolar bone had the lowest values in both DA and mean DA.

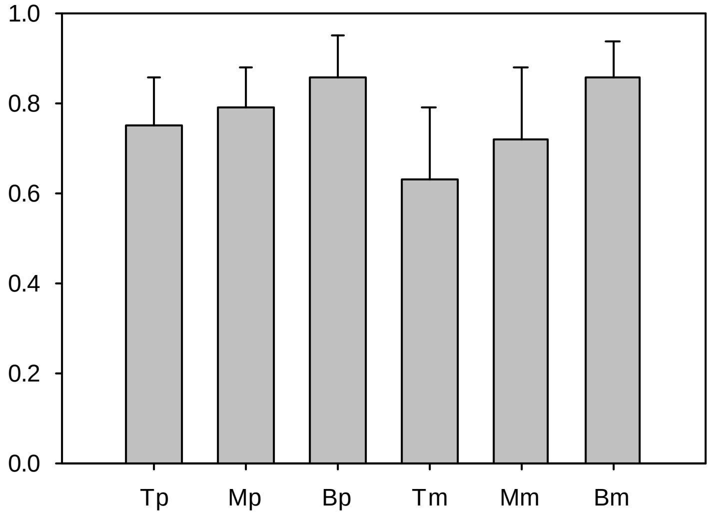

Fig. 9. The comparison of Degree of Anisotropy (DA) in the premolar and molar regions.

Structural morphology of trabecular bone is measured by structural model index (SMI) and its range varied from –0.49 to 3.02**.** The highest value of SMI and mean SMI could be found at the molar region inferior to the mandibular canal showing more rod-like structure and the lowest value at the molar region superior to the mandibular canal. The lowest mean SMI was measured at the alveolar bone of the molar region and has more plate-like characteristrics. This can also be confirmed by visual inspection of the specimen**.**

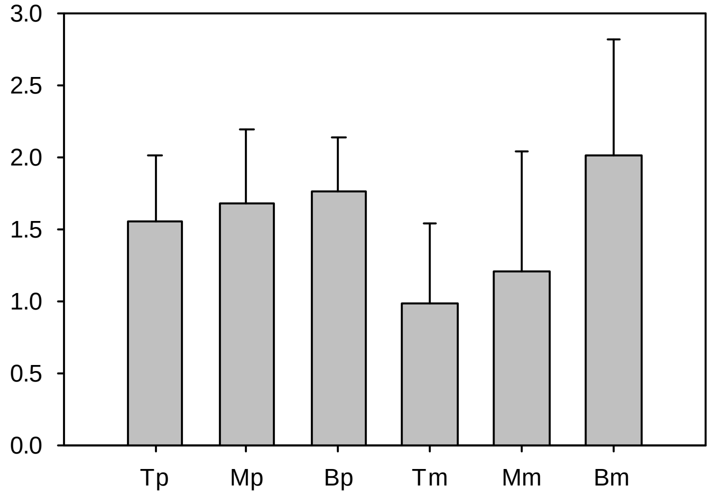

Fig. 10. The comparison of structural model index (SMI) in the premolar and molar regions.

Figure 11 to 16 indicate intraspecimen comparison of the alveolar and basal bone in both the premolar and molar region.

In comparison with basal bone superior to the mandibular canal, alveolar bone generally has higher values in BV/TV, Tb.N and lower in Tb.Sp(Fig. 11, 14).

In comparison between alveolar bone and basal bone inferior to the mandibular canal, alveolar bone has higher BV/TV and lower Tb.Sp and D.A in the premolar region(Fig. 12). In the molar region, there was higher values in BV/TV and Tb.N and lower in Tb.Sp, DA and SMI(Fig. 15).

On parametric values of trabecular bone above and below the mandibular canal in the premolar region, values of the superior region had higher BV/TV and Tb.N and lower Tb.Sp values which were all statistically significant(Fig. 13). Except for D.A and SMI values in the molar basal bone in the inferior region, with higher values than the superior region, all the other parametric measurements followed the general pattern of the premolar region(Fig. 16).

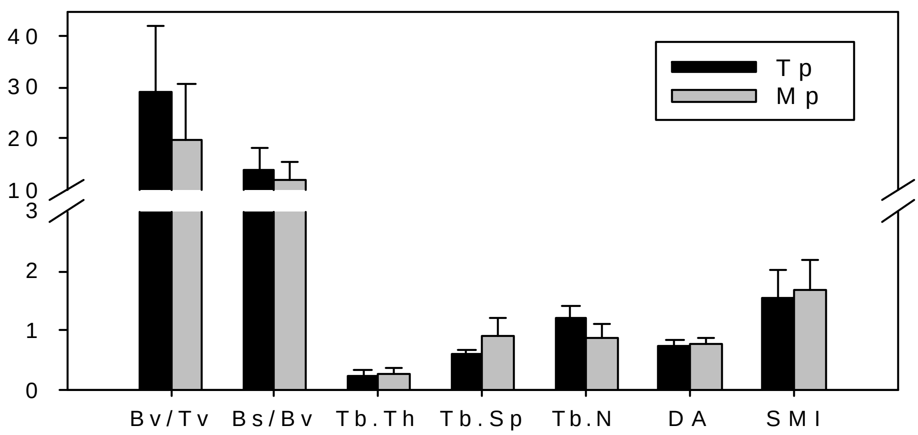

Fig. 11. Intraspecimen comparison of the alveolar trabecular bone and basal trabecular bone superior to the mandibular canal in the premolar region.

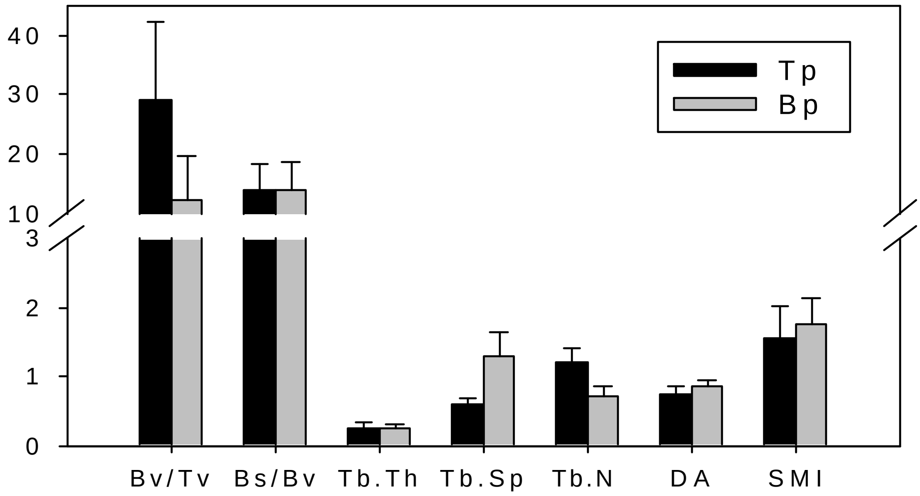

Fig. 12. Intraspecimen comparison of the alveolar trabecular bone and basal trabecular bone inferior to the mandibular canal in the premolar region.

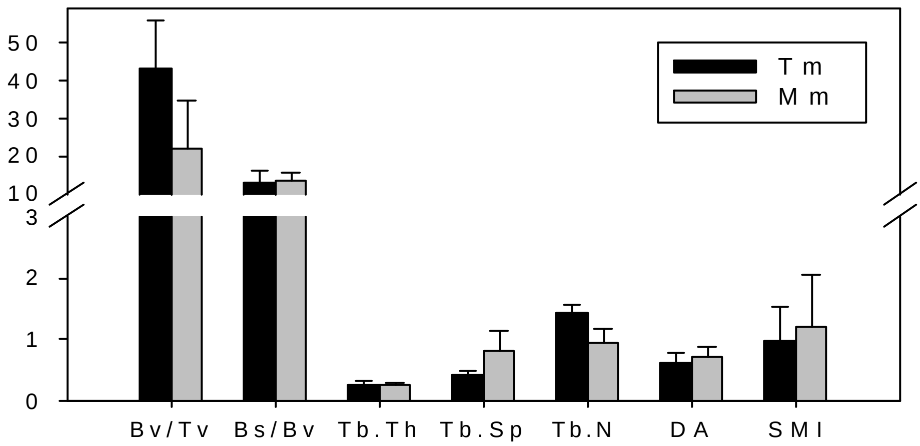

Fig. 13. Intraspecimen comparison of the inferior and superior basal trabecular bone in the premolar region.

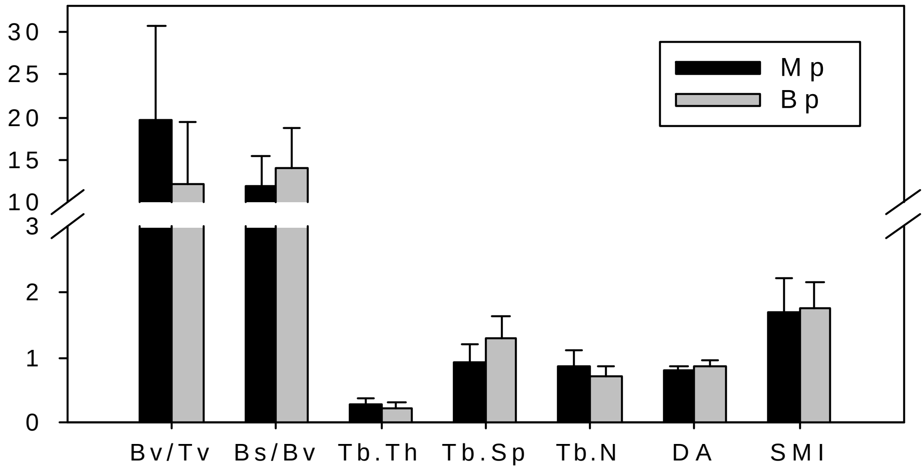

Fig. 14. Intraspecimen comparison of the alveolar trabecular bone and basal trabecular bone superior to the mandibular canal in the molar region.

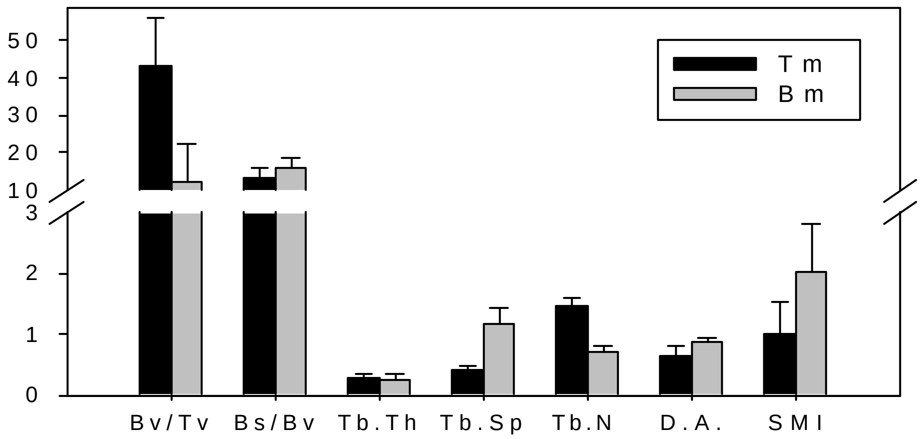

Fig. 15. Intraspecimen comparison of the alveolar trabecular bone and basal trabecular bone inferior to the mandibular canal in the molar region.

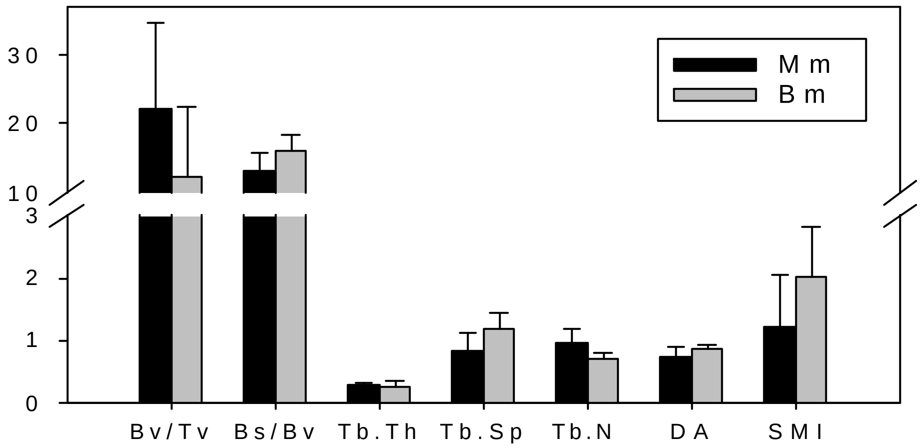

Fig. 16. Intraspecimen comparison of the inferior and superior basal trabecular bone in the molar region.

Each specific site of the premolar and molar regions within each individual were compared in Figure 17 to 19.

In the alveolar bone, the values of BV/TV and Tb.N were higher and Tb.Sp, DA and SMI were lower in the molar region(Fig. 17). However, there were no statistical significances in any parameters in the premolar and molar region of the basal bone specimen (M & B)(Fig. 18, 19).

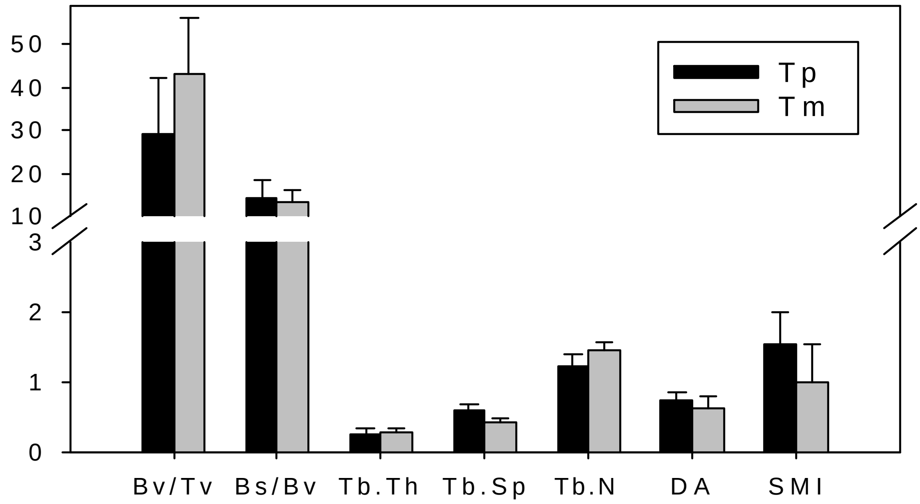

Fig. 17. Comparison of the alveolar trabecular bone between premolar and molar regions.

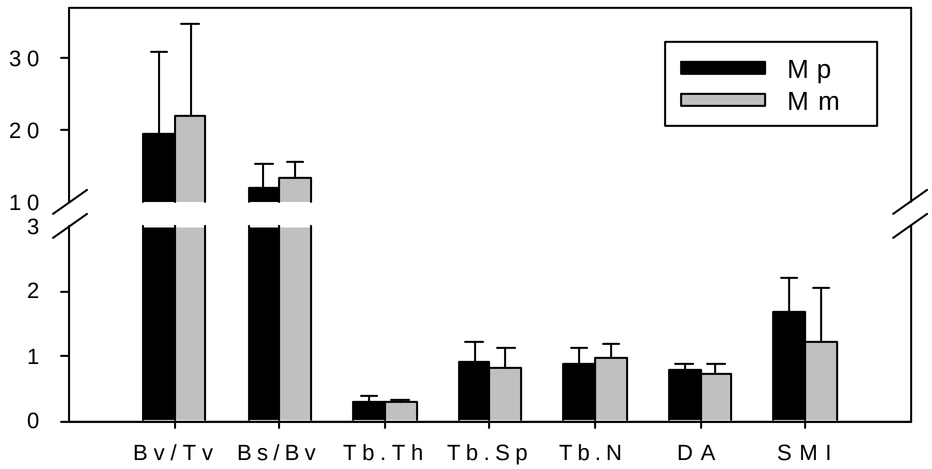

Fig. 18. Comparison of basal trabecular bone superior to the mandibular canal between premolar and molar regions.

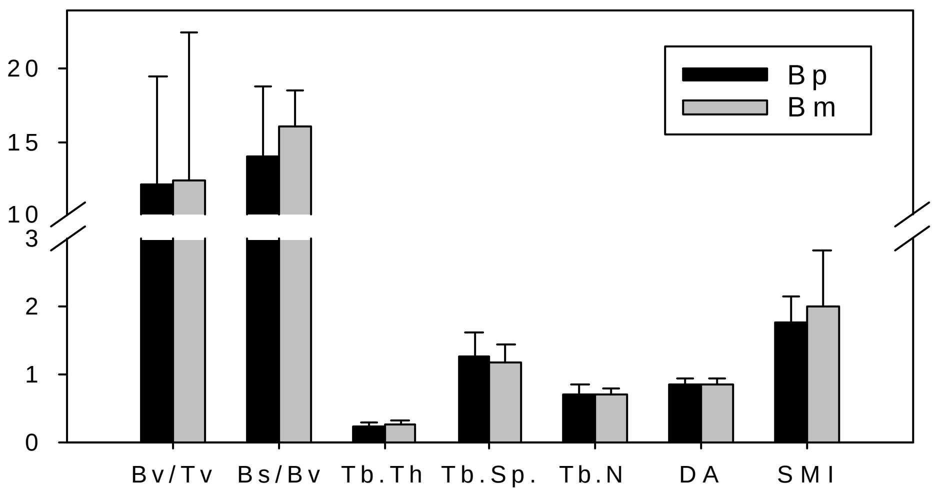

Fig. 19. Comparison of basal trabecular bone inferior to the mandibular canal between premolar and molar regions.

Relationships between BT/TV and other parameters

Pearson's correlation analysis was used between parameters to investigate which parameters might have a potential of giving structural information of the trabeculae beyond bone mass with BV/TV as the independent variables. Table 6 illustrates the coefficient of correlation between BV/TV and the other parameters. A linear correlation was found with either parameters and some relationships appear strong such as Tb.Sp, Tb.N and SMI**.**

Table 6. Pearson's correlation analysis between BV/TV and other parameters

r^2 *with BV/TV*	*BS/BV*	*Tb.Th*	*Tb.Sp*	*Tb.N*	*DA*	*SMI*
Premolar	0.399	0.166	0.478	0.352	0.312	0.533
Molar	0.453	0.344	0.717	0.638	0.534	0.639

p **<.05**

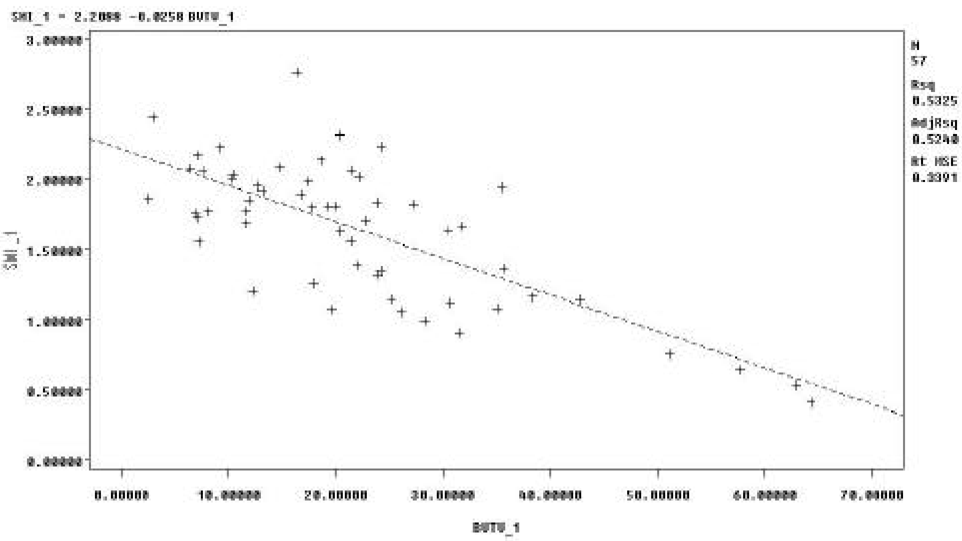

Fig. 20. Correlation between BV/TV and SMI in the premolar region.

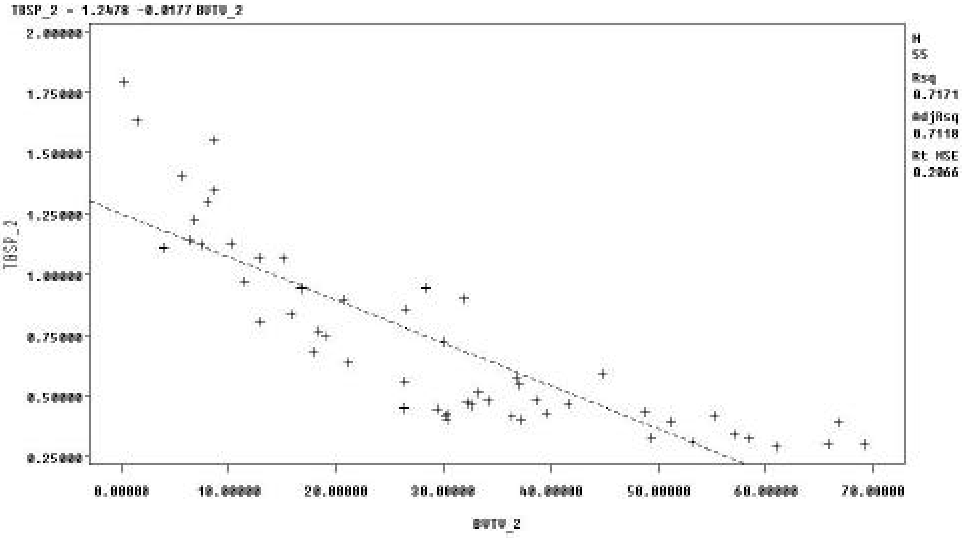

Fig. 21. Correlation between BV/TV and Tb.Sp in the molar region.

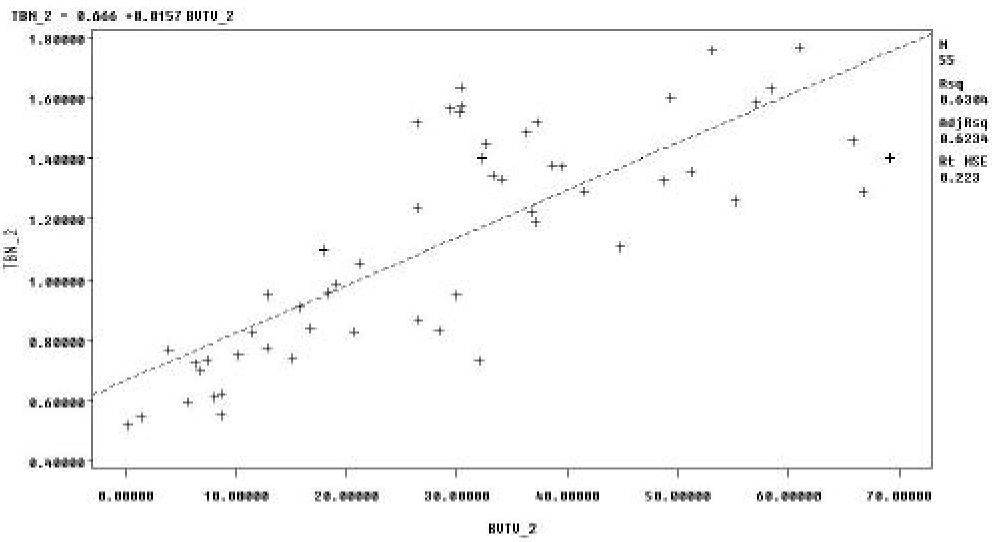

Fig. 22. Correlation between BV/TV and Tb.N in the molar region.

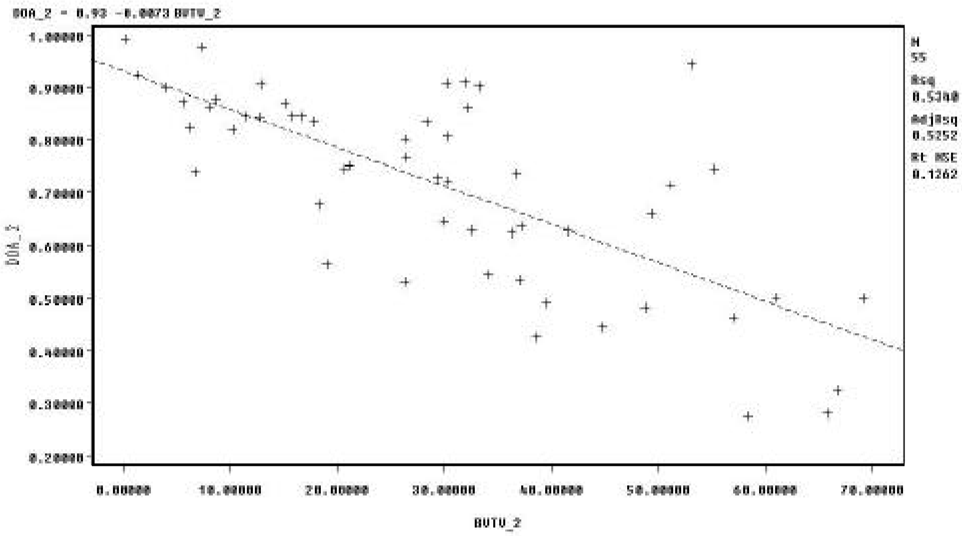

Fig. 23. Correlation between BV/TV and D.A in the molar region.

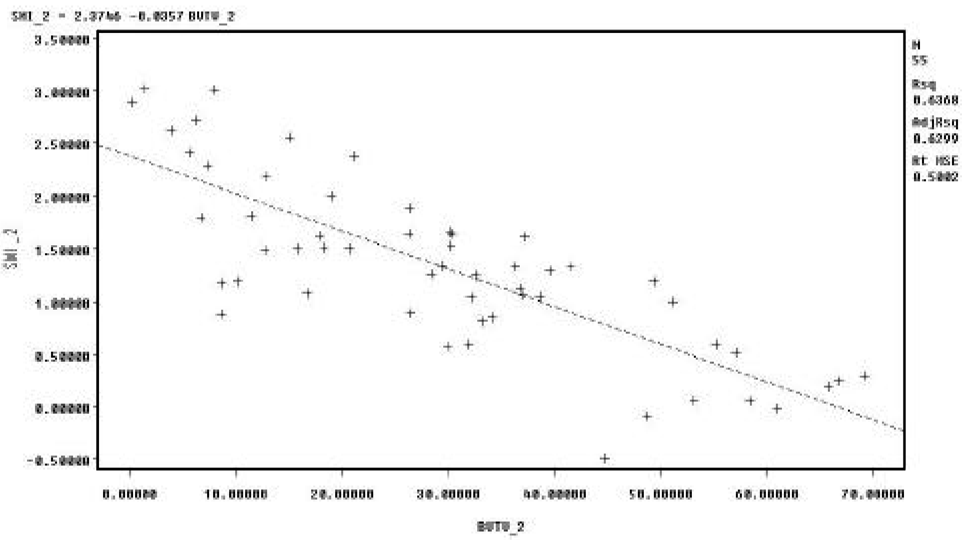

Fig. 24. Correlation between BV/TV and SMI in the molar region.

IV . DISCUSSION

Following the classic descriptions of trabecular bone architecture, more than half a century went by before new achievements were seen. Whitehouse[49, 50] provided detailed descriptions of trabecular architecture using SEM, and many other observations have been reported using various techniques.[31, 51, 52] Generally, structures have been described qualitatively such as "clearly connected" and "obviously disconnected." However, for analyzing biomechanical properties, more quantitative analysis is necessary. Therefore, several two-dimensional(2D) and three-dimensional(3D) measuring techniques have been developed. It is now possible to investigate the microarchitecture of trabecular bone directly without making assumptions on the structure type. Of these methods, micro-CT was initially developed to detect microstructural defects in ceramic materials. The system operates similarly to commercial computed tomography with some exceptions; Rather than rotating the x-ray source and detectors during data collection, as in clinical CT, the specimen is rotated. A 2D detector is used instead of a linear array of detector, thereby providing direct 3D image reconstructions. Of greater importance is the resolution of the system. Small specimens positioned very close to the x-ray source can be imaged with a higher resolution because the resolution increases with geometric magnification. In obtaining 3D images, greater number of cross-sectional images are attained without spending long hours and non-destructive methods in comparison to histological sectioning procedures as well.[34]

Comparing the morphometric analysis of human bone biopsies using micro-CT with histologic sections, high correlations of the results were obtained with the two procedures, providing further evidence that the newly devised micro-CT system was functioning effectively as a tool for the analysis of bony architecture[33, 37, 53].

In this study, a total of 30 specimen were measured using a micro-CT system and then analyzed. The sites of measurements were from premolar and first molar regions because premolar regions are one of the most commonly used sites in bone research[42, 54] and the first molar regions receives most occlusal force during its function and is one of most frequent places for implants.

The trabecular bone was divided into alveolar and basal bone area in this study. The separation in measurement was to compare any influence on trabecular bone from occlusal stress via the dentition. The reason behind the difference in the size of regions of interest(ROI) is that the alveolar bone area available for the measurement of trabecular bone is much smaller than in basal bone.[1, 55] Each area of the alveolar bone was divided into superior and inferior regions to maximize ROI and no significant differences were found between them. The ROI of the alveolar bone avoided lamina dura, edentulous sites, roots of the teeth, and other structural entities. ROI was positioned at least 2.5 mm apical to the crestal bone according to measurements defining the maximal range of effects of bone loss from periodontal disease– that is, beyond 2.5mm, there is no effect of bacterias on the alveolar bone[56].

Depending on the position of ROI in the mandible, the values of parameters vary greatly. To minimize bias in this study, the ROI was taken at the mid-point of the adjacent dentition.

In the basal bone, it was divided into two areas, superior and inferior to the mandibular canal. The reasons were to avoid any mispresented results by inclusion of the canal and the area superior to the canal is important when placing implants ,especially in molar regions. Despite of this, there were often limitations in the size of the ROI and there were some difficulties in obtaining specimens away from the mandibular canal. In these cases, the parameters could have been influenced by the presence of the mandibular canal and the adjacent cortical bone.

The first of these measurements, bone volume fraction(BV/TV), is a ratio of the bone volume to the total volume of ROI. Because bone, particularly trabecular bone, contains marrow spaces, this ratio will be less than 1. A solid cortical plate would approach a BV/TV of 1. In this study, the mean BV/TV ranged from 12.09% to 43.29%. Alveolar bone had the highest values, reflecting a compact structure that will resist external forces transferred through the dentition. The remaining structure of the specimen had a tendency to show general reduction in BV/TV as its distance increases from the alveolar bone and the most loosely structured trabecular bone was inferior to the mandibular canal that obviously receives the least amount of stress. In site specific comparisons, molar regions had more compact structure than premolar regions

The mean BV/TV in this study could not be compared with any other similar study as no corresponding studies were currently available. However, if values on other portions of the body were to be considered, the mandible had relatively high values(25-33% for iliac bone[28, 57]; 8.15-20.67% for the upper and lower limbs[58, 59]; 15-21% for mandibular condyle[60]**(**Table **7).** The variability between each study could be explained by differences in specimen such as different sites, age, sex, species and different methodology. In the mandible, the area used in this study receives most occlusal force and ,unlike the vertebrae, the forces in which it receives are in multidirectional impact forces. To overcome this, the author believes that the mandible must posses a more compact bony structure than any other part of body.

The mandibular bone volume varied greatly in many studies.[1, 61, 62]. In a study of Wowern et al,[1] there was no statistical difference of bone volume between premolar and molar regions. However, it was only focused on the mandibular body. In this study, the comparison between BV/TV of basal bone in the premolar and molar regions had no statistically significant difference, which supports the previous study mentioned by Wowern et al.

Table 7. Values of bone volume fraction (BV/TV) and bone surface density (BS/BV)

References	Bone	BV/TV(%) (Min-Max)	BS/BV(1/mm) (Min-Max)
Feldkamp[25]	Iliac bone	31.96-32.90	11.31-12.61
Goulet[60]	Human tibia, femur, ilium, spine, radius, and humerus	20±0.07 (6-36)	14.44±2.21 (10.75-21.02)
Urlich[61]	Calcaneus	11.65 (5.37-18.69)	21.82 (14.51-28.34)
	Femoral head	20.67 (8.30-31.68)	15.25 (8.88-21.94)
	Iliac crest	15.22 (5.73-21.88)	17.63 (10.30-23.72)
	Lumbar vertebrae	8.15 (4.35-12.33)	23.37 (18.74-32.45)
Ito[62]	Iliac bone	25-32	12.73-15.21
Giesen[63]	Human condyle	17±5 (0.15-0.21)	20.5±3.4 (18.3-23.0)

Similarly, bone surface density (BS/BV) is a ratio of the bone surface area to the total bone volume. The more surface area there is and the higher the BS/BV ratio. In examples of a same BV/TV with higher BS/BV are; a rough trabeculae structure, perforated trabecular bone plate or low plate-to-rod ratio, etc. The highest BV/TV in alveolar bone of the molar region with the second lowest value of BS/BV could be possibly explained by, either that the trabeculae is thick or the bone consists mainly of wide plate-like structure. In both premolar and molar regions of basal trabecular bone had low BV/TV and high BS/BV. It is highly probable that the trabecular bone consist of loosely arranged rod-like structure in those regions. Alveolar trabecular bone of the premolar region has the second highest BV/TV following the alveolar trabecular bone of the molar region but BS/BV is also high, meaning that the trabecular bone is thinner and structured more rod-like mixed type could be concluded.

Basal bone superior to the mandibular canal had relatively low BS/BV and

BV/TV which also indicates a mixed type of structure with a possibly fewer trabeculae than in the alveolar region. In this study, however, the range of BS/BV was 12.02-16.08mm^2/mm^3 and the difference in values and effects were minimal.

When comparing the result of this study with others, unlike the values of BV/TV, the BS/BV did not show much difference to the values of BS/BV in different parts of the body such as the upper and lower limbs[60], femoral head[61] and iliac bone[28,57-59] (Table 7). However, when comparing with the values of human mandibular condyle, the mandible had relatively lower values, indicating that the mandible might be composed of relatively thicker trabeculae than the condyle [60].

In the body of the mandible, according to Von Wowern[1] the trabecular bone of the premolar region consisted of coarsely woven bone and the molar region consisted of a more delicately woven bone, which is somewhat comparable with our study.

When the resolution is raised, the bone perimeter increases which ,in turn, increases BS/BV. Therefore, care must be taken when comparing with results from other studies with different resolutions[5]. In this study, all the specimen were measured under resolution of 21.3 ㎛. Müller et al. suggested that the resolution should be around 20 ㎛ for an accurate estimation of structural indices such as trabecular thickness or trabecular separation because the average width of a human trabecular bone is 132.4±27.9 ㎛ and this suggestion has been accepted and applied to this study.

Trabecular bone thickness (Tb.Th), Trabecular bone separation (Tb.Sp) and Trabecular bone number (Tb.N) are measurements of the mean thickness, separation and density of trabeculae within the specimen respectively. Together, these measurements give information about the amount of bone in the specimen as well as its organization. For two equal amounts of bone cubes, as given by BV/TV, the distribution and organization of bone within these cubes can be quite different. For example, one cube might have thick trabeculae spaced farther apart; Tb.Th and Tb.Sp would be greater in this cube compared with the second bone cube.

The alveolar bone of the molar region has high Tb.Th, indicating structurally thick trabeculae and may be one of the reason for higher BV/TV. In the alveolar bone of the premolar region, Tb.Th is not thick in comparison with other sites. The high BV/TV of the premolar alveolar bone, therefore, should be explained for another reason rather than thick trabeculae.

The trabecular bone superior to the mandibular canal of the premolar region is the highest in width but comparatively low in BV/TV and BS/BV. This reflects that the thick trabecular bone is loosely packed(low Tb.N). Tb.Th inferior to the mandibular canal was low and it might be the reason for BV/TV. However, in this study, the Tb.Th of the mandibular trabecular bone ranged between 0.24-0.29mm with little variation which would not have had much influence over BV/TV.

Alveolar bone in the molar region had the highest trabecular number(Tb.N) where high BV/TV could be expected and followed by alveolar bone in the premolar region.

Trabecular bone inferior to the mandibular canal had low Tb.N, which can be concluded that the bone has a loose trabecular bone structure.

The sequence of Tb.N in size corresponds to BV/TV. Therefore, areas with high BV/TV often had a high Tb.N.

Tb.Sp had a negative relationship with BV/TV and Tb.N. In alveolar bone of molar regions with low value of Tb.Sp had the meaning of a closely compact trabecular bone structure, but basal bone with high value had a loosely arranged relationship. Summarizing the above results, a possible reason of the high BV/TV is mainly due to high number of the trabeculae. The effect of bone thickness, however, may be minimal as the difference is small.

Published measurements of trabecular structure have a broad range, owing to the different sources of bone and methods (Table 8). Our findings of trabecular thickness in the mandible are rather similar to one study about the mandibular condyle[63] (0.27-0.34mm). In other studies on the iliac bone or upper and lower limbs, the values were lower than mandibular trabecular bone, which can be related to the thicker trabeculae than in other skeletal bones. However, it should be considered that the model independent Tb.Th used in this study is systemically higher than Tb.Th assessed with the plate-model assumption used in most other studies. The reason for this is seen in the deviation of the trabecular structure from the ideal plate model. There are always rods present, which cause the surface-to-volume ratio to be higher at a given thickness with the consequence of a smaller apparent trabecular thickness derived from BV/BS. Therefore, even in the pronounced plate-like structure as in the alveolar bone of the first molar area, the trabecular thickness derived from ideal plate model is underestimated. As expected, the larger underestimation might be measured in the basal bone area where the SMI is higher. Similar observations were made in two dimensions, when directly and indirectly calculated trabecular widths were compared.[64]

Trabecular separation (Tb.Sp) ,ranged from 0.42mm to 1.28mm, did not have much difference to the other results (Table 8).

The number of trabeculae per mm in the mandible is relatively low, 0.70-1.45/mm, compared to other studies (mandibular condyle, 1.66±0.26/mm[60], human iliac bones, 1.78-2.03/mm[28], 1.70-1.94/mm[57], proximal tibiae, 1.58-1.72/mm[65] and long bones, 1.39±0.32/mm[58]). Taken together, these results suggest that the mandible has a more or less dense trabecular bone, which is probably relatively strong. As the thickness of the trabeculae is greater, it can be explained indirectly that this area is where the stress concentrates[66]. Especially in the molar region where the occlusal force concentrates, the structure was similar to center of the superior regions of the condyle, which has the thickest, the least separated, and the most numerous trabeculae structure[60, 63].

Table 8. Values of trabecular thickness (Tb.Th), trabecular separation (Tb.Sp) and trabecular number (Tb.N)

References	Bone	Tb.Th	Tb.Sp	Tb.N
Feldkamp[28]	Human iliac	0.16-0.18		1.78-2.03
Goulet[58]	Human tibia, femur, ilium, spine, radius, and humerus	0.14±0.02 (0.10-0.19)	0.64±0.24 (0.32-1.67)	1.39±0.32 (0.61-2.06)
Urlich[59]	Calcaneus	0.127±0.017 (0.102-0.169)	0.684±0.109 (0.456-0.982)	1.45±0.20 (1.00-2.09)
	Femoral head	0.172±0.029 (0.120-0.257)	0.706±0.110 (0.480-0.984)	1.42±0.21 (0.98-1.91)
	Iliac crest	0.150±0.027 (0.101-0.225)	0.754±0.143 (0.523-1.306)	1.39±0.24 (0.79-1.98)
	Lumbar vertebrae	0.123±0.016 (0.082-0.157)	0.800±0.133 (0.612-1.269)	1.26 ±0.19 (0.77-1.63)
Ito[57]	Iliac bone	0.15-0.16	0.36-0.45	1.70-1.94
Giesen[60]	Human condyle	0.10±0.02 (0.09-0.11)	0.52±0.13 (0.45-0.56)	1.66±0.26 (1.60-1.81)
Hongo[63]	Human mandibular condyle	0.27-0.34		
	Human lumbar vertebrae	0.35-0.50		
Ding[65]	Proximal tibia	0.17±0.03 (0.16-0.19)		1.63±0.22 (1.58-1.72)
Teng[66]	Pig condyle	0.13-0.18	0.23-0.27	2.4-2.9

Highly accurate stereological measurements of “anisotropy” are possible because of the ability to obtain direct analysis in three dimensions. “Isotropy” relates to trabecular organization and expresses the degree of preferred orientation. An isotropic structure has no preferred orientation, whereas increasing anisotropic structures become more and more polarized. Thus, in a trabecular bone specimen with a high degree of anisotropy (DA), the trabecular orientation would be polarized along one axis. When an external force is applied to the trabecular bone, it will tend to remodel, so that they are polarized parallel to the axis of that force. For example, a change in mastication characteristics affects internal bone structure and remodeling capacity of the mandible.[67] Thus, the measurement of anisotropy allows us to quantitatively correlate the effects of environmental force and bone remodeling.

DA was the lowest at the alveolar bone of the molar region with low polarity but highest in the basal bone inferior to the mandibular canal in both premolar and molar regions. The lower DA of the alveolar bone in the molar region can be explained that the alveolar bone in the molar region receives forces from all directions through complicated functions such as mastication unlike a long bone such as the tibia or vertebrae that receives forces mainly in the vertical direction. This diverse direction of force upon the bone might cause lower polarity. That is, to sustain the resistance to the forces on the trabecular bone, the structure of the bone is in multidirectional, highly connected structure that is more mechanically stable[36]. Bones under multiple load condition such as the mandible, condyle and the vertebrae characteristically tends to have the structure with higher BV/TV, Tb.N and lower DA[60, 68] support this explanation. The range of DA applied in this study is from 0 to 1, 0 being the perfect isotropy and 1 having all the trabecular bone in one direction. However as the scale used in this study is different from that of other studies, it prevents from a direct comparison and this remains a problem to be solved in the future.

The structural model index(SMI) was calculated from three-dimensional images using an analysis of the triangulated bony surface of the structure. The SMI characterized a three-dimensional bone structure composed of a certain amount of plates and rods. The SMI was defined as a non-metric value between 0 and 3. In an ideal plate structural model, the SMI value was 0, and in an ideal cylindrical rod structure, the SMI value was 3, independent of the physical dimensions of the structure. The SMI would lie between 0 and 3 when a structure consisted of both plates and rods, depending on the ratio of rods and plates[47].

The low SMI of the alveolar bone in the molar region reveals a somewhat plate-like structure and basal bone of both premolar and molar regions had high values that show relatively rod-like structure. The plate-like trabecular pattern in the molar regions might be explained to be designed to resist external forces. This is accompanied with the favorable root shape and large root surface area that is able to distribute stress to adjacent structures.

Basal bone inferior to the mandibular canal in both premolar and molar regions are mainly rod-like structure, which is not suitable to resist the stress but the cortical bone thickness of basal bone is large enough to make the internal trabecular structure to become disuse atrophy. From the results mentioned, both alveolar and basal trabecular bone of the mandible is properly designed to resist external forces with minimum bone volume with maximum adaptation.

The negative SMI values in this study originate from the very dense specimen such as alveolar bone in the molar region with a concave plate-like structure. When a specimen has a value of greater than 3.0, unlike a negative SMI, hardly any bone structure could be found and the trabecular bone is mostly consisted of rod-like structures (Fig. 4).

In a study on proximal tibia, with an increase in age, rod-like structures increases by SMI value of 0.70±0.45 to 1.07±0.54.[65] When the structure of proximal tibia is compared with the mandible, tibia had thinner and more plate-like structures. It may have been contributed by one directional external force on the bone, which produce primarily trabecular plate arrangement polarized to the axis of the force. In the mandible where the force applied is multidirectional, the trabeculae is thicker with low polarity to obtain an adequate resistance during its function.

When relationships of other parameters with BV/TV are made, Tb.Sp, SMI and Tb.N had relatively high correlation but Tb.Th had lower correlation with BV/TV.

The above statement is consistent with the study of Uchiyama[33] that there were closely correlated between BV/TV, Tb.N and Tb.Sp. In a study of Rüegsegger[36], there was close linear correlation between BV/TV and SMI but less with Tb.Th. It is claimed from the results that the bone loss is not due to the thinning of trabecular bone but due to changes in the small plate-to-rod ratio or loss of trabeculae. Another reason for the lower correlation coefficient of Tb.Th versus BV/TV than that of Tb.Th*, which is calculated from the assumed plate model, is that Tb.Th* is dependent on BV/TV because it can be explained by the definition of Tb.Th*, which contains also BV, whereas the determination of Tb.Th is really independent from that of BV/TV. As a result, we think that the larger variation of the data seen for the directly determined Tb.Th is closer to reality.

Summarizing the above facts, the alveolar bone has high bone mass that is well distributed, plate-like structure with lots of trabecular bone to maximize the resistance to multidirectional external forces. This property of alveolar bone was more clearly observed in the molar region. As the measurements were taken closer to the basal bone, the bone mass and trabecular number decreases creating loose, rod-like structures. In the basal bone, the differences between premolar and molar regions were unclear.

Based on these results, the trabecular bone in the premolar and molar regions seems to be well designed to manage its masticatory function. In majority of implant treatment cases, the primary stability is achieved with trabecular bone. It is advisable to gain initial stability within alveolar bone than basal trabecular bone according to the results. Therefore placing wide diameter implants with shorter length would be advantageous in biomechanical aspect than standard implants with longer length.

Because micro-CT can present the full three-dimensional data of the trabecular bone structure around an oral implant in a digital format, these data can be used to create accurate finite-element(FE) models of the bone-implant system. Whereas in previous FE studies, trabecular bone was modeled as a continuum, it will now be possible to model individual trabeculae and to study the stress transfer at the interface from the implant to individual trabeculae.

Recently, it has been demonstrated that the mechanical properties of trabecular bone can be calculated using the voxel-grid as the input for microstructural finite-element models[69-71].

The sample size in this study was small and the information on sex or age was not available for morphometric analysis. A further study with larger sample size, including trabecular bone of both incisors and canine would be valuable. Micro-CT also has some limitations; Scanning and reconstruction of the specimen takes a long time. The equipment is expensive and 3D reconstruction requires a high degree of computer expertise. The technique is not suitable for clinical use, but is a powerful tool for research into various aspects of the dental field, including endodontics, periodontics, orthodontics and implantology[72-74].

Micro-tomographic imaging is a nondestructive, fast, and very precise procedure that allows the measurement of trabecular and compact bone in unprocessed biopsies as well as an automatic determination of morphometric indices. The instrument is compact and fully automated, and may be of considerable help in basic as well as in clinical research.

V. CONCLUSION

The purpose of this study was to investigate the three-dimensional trabecular structure of the alveolar and basal bone in the lower premolar and molar regions, and the differences were compared. For this study 30 specimens were prepared and scanned using microcomputed tomography (Skyscan-1072, SKYSCAN, Antwerpen, Belgium) and 3D image consisted of voxels sized 21.3x21.3x21.3μm^3 was reconstructed. From these images of specimen, bone volume fraction (BV/TV), bone surface density (BS /TV), Trabecular thickness (Tb.Th), Trabecular separation (Tb.Sp), Trabecular Number (Tb.N), Degree of Anisotropy (D.A) and Structural Model Index (SMI) were measured and the following conclusions were made.

1. In the premolar region, the alveolar trabecular bone had higher values of bone volume fraction and trabecular number but lower in trabecular separation than the basal bone superior to the mandibular canal, where compacted alveolar bone structure with lots of trabecular bone could be concluded.
2. In the comparison between alveolar bone and basal bone inferior to the mandibular canal, the trabecular bone that was inferior to the mandibular canal had all values similar to the values of the superior region other than a low degree of anisotropy, which was statistically significant.
3. When the basal bones superior and inferior to the mandibular canal were compared, bone volume fraction and trabecular number at the superior region had high values that were statistically significant. Trabecular separation and degree of anisotropy, on the other hand, were low which implies that the basal bone in the superior region were more compact in structure.
4. Except for the molar region, where a higher structural model index value of trabecular bone in inferior than superior to the mandibular

canal, the remaining relationships were similar to those of premolar regions.

5. When same sites of molar and premolar regions were compared, a higher bone volume fraction and trabecular number were found in the molar alveolar region implying that the molar alveolar bone has a compact structure. Trabecular separation, degree of anisotropy and structural model index in the molar regions had lower values and it could be concluded that this area had trabecular bone which has more plate-like structure and less polarity of trabecular bone than the premolar region, indicating adequately remodeling zone against external forces.
6. In basal bone, all parameters between premolar and molar regions were statistically not significant.
7. In the relationships between bone volume fraction and other parameters, linear correlations were found with all the parameters. In some relationships had higher correlation than others, and they were trabecular separation, trabecular number and structural model index.

In reference to the results above, it can be concluded that the structure of the mandible is appropriately designed to perform and withstand occlusal forces and masticatory function. It is more clearly noted in the molar regions.

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LEGENDS

Fig. 1. Schematic illustration of micro-CT system

Fig. 2. Region of interest to be measured and 3D reconstruction procedure using micro-CT system

Fig. 3. Micro-CT images of the trabecular bone in the mandible

Fig. 25. Alveolar bone area showing negative value of SMI (-0.015) and basal bone inferior inferior to mandibular canal showing SMI value of higher than 3 (3.016)

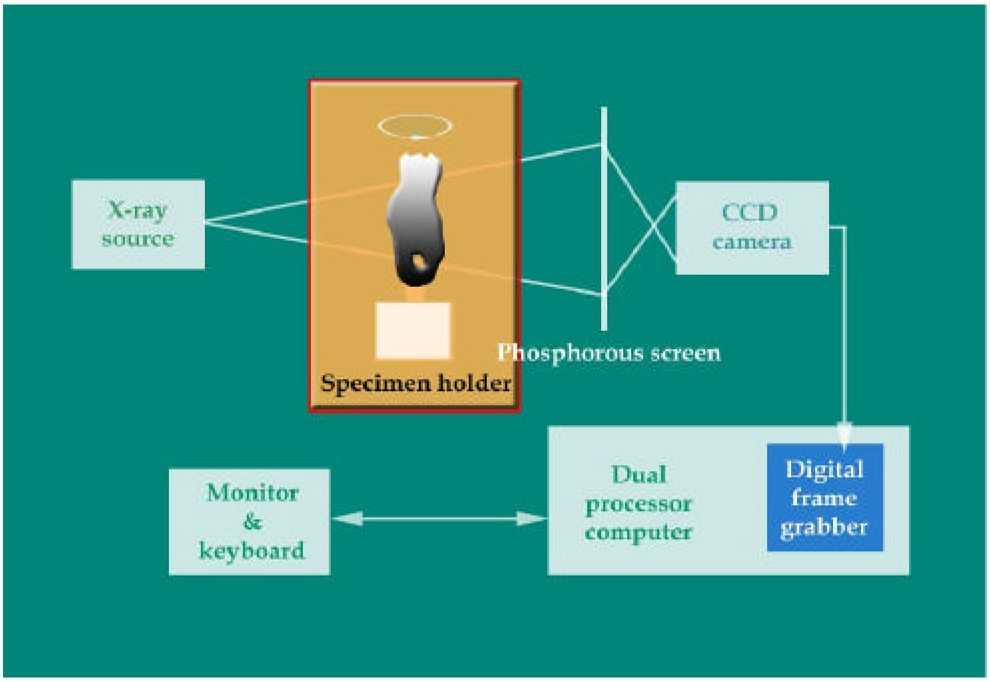

Fig. 1. Schematic illustration of micro-CT system.

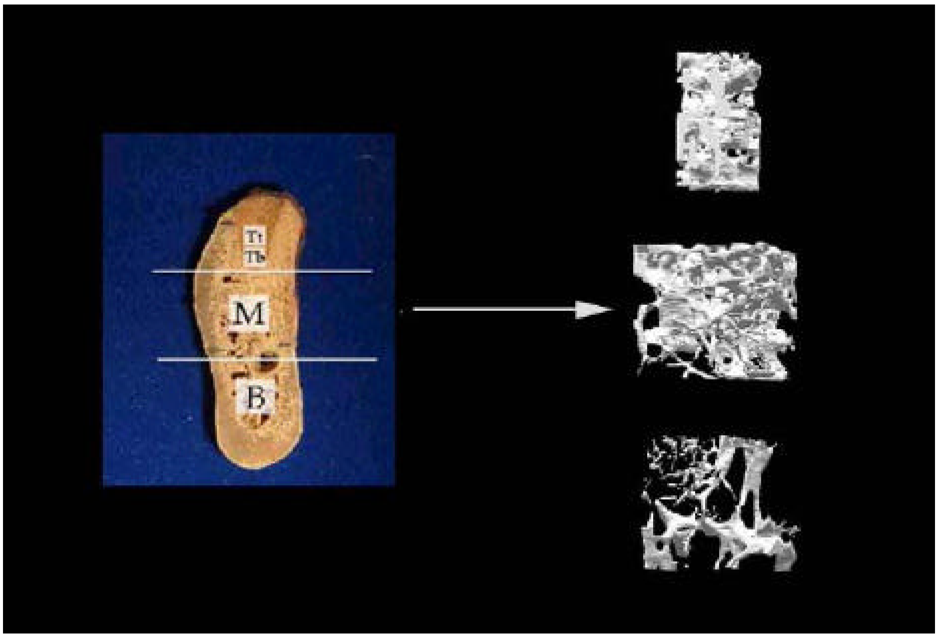

Fig. 2. Region of interest to be measured and 3D reconstruction procedure using micro-CT system.

Alveolar bone area

Basal bone superior to
mandibular canal

Basal bone inferior to
mandibular canal

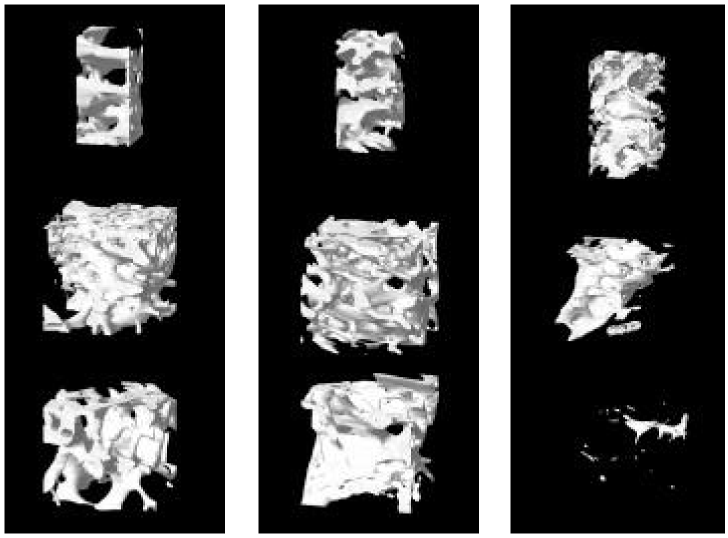

Fig. 3. Micro-CT images of the trabecular bone in the mandible (premolar region).

Alveolar bone area

Basal bone superior to
mandibular canal

Basal bone inferior to
mandibular canal

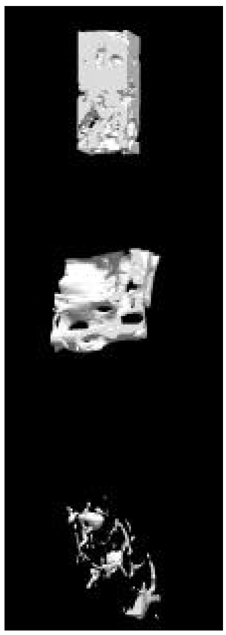

Fig. 25. Alveolar bone area showing negative value of SMI (-0.015) and basal bone inferior to mandibular canal showing SMI value of higher than 3 (3.016).

국문 요약

미세 전산화 단층촬영을 이용한 하악 소주골형태의 3 차원적 분석

하악골은 신체의 다른 부위와 비교하여 여러 가지 형태적 기능적특징을 가지고 있다. 하지만 가장 큰 특징은 치아가 존재하는 것이다. 이러한 치아의 존재로 인하여 교합력과 같은 외력이 소주골에 직접 전달이 되어 골량이나, 골 구조등에 영향을 미친다. 신체의 골 구조에 대해서는 많은 학자들이 연구하였고 그 중요성에 대하여 언급을 하였으나 하악골에서는 치조골흡수, 치아상실이나 Implant 성공률등에 대하여 골량이나 골 밀도에 관계하여 연구를 했지만 골 구조와 관계하여서는 거의 관심을 기울이지 않은 것이 사실이다.
따라서 본 실험은 하악소주골의 3 차원적인 구조를 분석하여 저작기능과의 관련성을 살펴보고 보다 정확한 생체역학연구를 위한 기초자료를 제시하여 Micro-CT 의 치의학분야에 대한 응용가능성을 위하여 소구치 및 대구치시편을 Skyscan 1072(SKYSCAN, Antwerpen, Belgium)를 이용하여 치조골부위와 하치조신경을 기준으로 한 상,하 두 부분의 기저골부위를 촬영 및 분석하여 다음과 같은 결과를 얻었다.

1. 치조골부위에 존재하는 소주골이 기저골부위보다 골량 및 골 소주가 많았으며 골 소주의 간격이 좁아서 치조골부위가 보다 치밀한 구조로 이루어져 있었다.
2. 하치조신경을 기준으로 한 상방 과 하방의 기저골의 비교에 있어서는 상방의 기저골에서 높은 골량 및 골 소주의 개수를 나타내고 있으며 낮은 소주간 거리 및 이방성을 나타내어 하

방의 기저골보다 치밀한 구조를 보이고 있었다.

3. 치조골에 대한 소구치와 대구치의 비교에 있어서는 대구치의 치조골부위에서 소구치의 치조골부위보다 골량 및 골 소주의 개수가 많았고 낮은 골 소주간의 거리, 이방성의 정도와 낮은 구조형태지수를 나타내어 보다 판상의 형태로서 치밀하게 연결이 되어 교합력을 비롯한 외력에 보다 잘 저항할 수 있는 구조로 되어 있음을 알 수 있었다.
4. 기저골에 대한 소구치와 대구치의 비교에 있어서는 모든 계측항목들이 차이가 없었다.
5. 골량과 다른 계측항목 들과의 상관관계에서는 골 소주간의 거리, 골 소주 개수와 구조형태지수가 비교적 높은 상관관계를 나타내었다.

이와 같은 결과로 볼 때, 하악의 소주골은 치아를 통한 외력에 잘 견딜 수 있는 기능적인 구조로 적절하게 배열이 되어 있는 것으로 여겨지며 대구치 부위에서 보다 명확하였다. 또한 이와 같은 사실은 생역학적 분석을 비롯한 하악골의 연구 시에 고려되어야 할 사항으로 생각된다.

핵심 되는 말 : 미세전산화 단층촬영, 하악골, 골 구조, 소주골