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The effects of cortical bone thickness and trabecular bone strength on non-invasive measures of the implant primary stability: an in vitro study

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Complete List of Authors:	Hsu, Jui Ting; China Medical University and Hospital, School of Dentistry Fuh, Lih Jyh; China Medical University and Hospital, School of Dentistry Tu, Ming Gene; China Medical University and Hospital, School of Dentistry Li, Yu Fen; China Medical University and Hospital, Institute of Environmental Health Chen, Kuan Ting; China Medical University and Hospital, Biostatistics Center Huang, Heng Li; China Medical University and Hospital, School of Dentistry
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Title: The effects of cortical bone thickness and trabecular bone strength on non-invasive measures of the implant primary stability: an in vitro study

Jui-Ting Hsu [1], Lih-Jyh Fuh [1], Ming-Gene Tu [1], Yu-Fen Li[2,3], Kuan-Ting Chen[2],
Heng-Li Huang [1*]

Authors' affiliations:

[1] School of Dentistry, China Medical University and Hospital, 91 Hsueh-Shih Road, Taichung 404, Taiwan.

[2] Biostatistics Center, China Medical University and Hospital, 91 Hsueh-Shih Road, Taichung 404, Taiwan.

[3] Institute of Environmental Health, China Medical University and Hospital, 91 Hsueh-Shih Road, Taichung 404, Taiwan.

Correspondence address:

Heng-Li Huang, Associate Professor; Address:School of Dentistry, College of Medicine, China Medical University and Hospital, 91 Hsueh-Shih Road, Taichung 40402 Taiwan; Tel. 886-4-22053366 ext. 2306; Fax. 886-4-22014043; E-mail address: hlhuang@mail.cmu.edu.tw

Abstract

Purpose: This study investigated how the primary stability of a dental implant as measured by the insertion torque value (ITV), Periotest value (PTV), and implant stability quotient (ISQ) is affected by varying thicknesses of cortical bone and strengths of trabecular bone. **Materials and Methods:** Four synthetic cortical shells (with thicknesses of 0, 1, 2, and 3 mm) were attached to four cellular rigid polyurethane foams (with elastic moduli of 137, 47.5, 23, and 12.4 MPa) and one open-cell rigid polyurethane foam which mimic the osteoporotic bone (with an elastic modulus 6.5 MPa), to represent the jawbones with various cortical bone thicknesses and strengths of trabecular bone. A total of 60 bone specimens accompanied with implants was examined by a torque meter, Osstell resonance frequency analyzer, and Periotest electronic device. All data were statistically analyzed by two-way analysis of variance. In addition, second-order nonlinear regression was utilized to assess the correlations of the primary implant stability with the four cortex thicknesses and five strengths of trabecular bone. **Results:** ITV, ISQ, and PTV differed significantly ($p<0.05$) and were strongly correlated with the thickness of cortical bone ($R^2>0.9$) and the elastic modulus of trabecular bone ($R^2=0.74$–0.99). **Conclusions:** The initial stability at the time of implant placement is influenced by both the cortical bone thickness and the strength of trabecular bone; however, these factors are mostly nonlinearly correlated with ITV, PTV, and ISQ. Using ITV and PTV seems more suitable for identifying the primary implant stability in osteoporotic bone with a thin cortex.

Keywords: implant primary stability, cortical bone thickness, strength of trabecular bone, insertion torque, Periotest, resonance frequency analysis

Introduction

The dental implant has become a popular treatment for oral rehabilitation following the introduction of osseointegration by Brånemark et al.[1]. Many studies have reported high success rates for dental implant treatment in the mandible[2,3]. However, the rate of implant loss is still higher in other locations, such as the posterior maxilla[3], which has been attributed to low bone strength. Some reports have considered bone quality and quantity to be important determinants of success for both conventional and immediate-loading implants[4,5].

Primary stability is one of the factor prognostic of the osseointegration of dental implant[6]. A greater primary stability means less micromotion between the implant and bone, which promotes osseointegration during the healing period. The initial instability of an implant may result in excessive micromotion[7] that increases the risk of poor osseointegration. Many factors reportedly influence the primary stability of an implant, such as the surgical technique[8], the length, diameter and geometry of the implant[9-12], the roughness of the implant surface[13,14], the bone-to-implant contact (BIC) ratio[15], and the local amount of the host bone and its quality[16,17]. Several noninvasive techniques – including the peak insertion torque value (ITV), Periotest value (PTV), resonance frequency analysis (RFA) (usually evaluated as the implant stability quotient, ISQ)[17], and peak removal torque value (RTV)[14,18] – have been proposed for diagnosing stability problems of an implant and for predicting implant success in both the clinic and the laboratory.

High implant stability at the early stage of implant placement is essential, since this greatly influences the probability of success of implant therapy. The classification of bone quality as types 1–4 by Lekholm and Zarb[19] has been applied clinically for evaluating the bone types of patients before implant placement. There are reports that bone was lost in only 3% of implants placed in bone of type 1, 2, or 3, whereas the failure rate was 35% in type-4 bone, corresponding to a thin cortical shell and softer trabecular bone[20]. In addition, the implant stability is lower in type-4 bone than in bone of other qualities[21]. The cortical thickness and the strength (or density) of trabecular bone appear to be very important, since insufficient implant anchorage is a problem in bone that is mechanically weak or even osteoporotic. However, using the Lekholm and Zarb classification only provides a rough assessment of the quality and quantity of jaw bone, and hence the precise relationships of bone quality and quantity with implant stability are still unclear.

Osteoporosis is associated with decreases in bone mass and density and a consequent increase in bone fragility that increases the risk of fracture[22]. Even though there is a general consensus that osteoporosis is not a risk factor for implant osseointegration[23,24], recent studies have found that osteoporosis is significantly associated with early implant failure[25,26]. Osteoporotic trabecular bone can be characterized as type-4 bone, which is poor quality (i.e., low strength). However, even bone that is not osteoporotic can exhibit a low stiffness. The open cell structure of osteoporotic bone might reduce the initial implant stability, but no study has characterized the differences in implant stability in soft trabecular bone with and without osteoporosis.

The objective of this study was to elucidate the precise correlations between bone quality and quantity (e.g., various thicknesses of cortical bone and strengths of trabecular bone) with primary implant stabilities by measuring ISQ, ITV, and PTV in cellular foam bone samples. This study also examined differences in implant stabilities between of trabecular bone with a normal (cellular) structure and an osteoporotic (open-cellular) structure.

Materials and Methods

Specimen preparation

Commercially available synthetic cortical shells (models 3401-07, 3401-01, and 3401-02; Pacific Research Lab), cellular rigid cancellous specimens (models 1522-09, 1522-10, 1522-11, and 1522-12; Pacific Research Laboratory., Vashon Island, WA, USA), and open-cellular rigid cancellous specimens (model 1522-505, Pacific Research Laboratory) were used to represent varying strengths of trabecular bone (Fig. 1) with different thickness of cortical bone. For the open-cellular cancellous specimen, it was used to simulate the osteoporotic cancellous bone. The cortical shells had thicknesses of 0, 1, 2, and 3 mm with a elastic modulus of 16.7GPa. The moduli of elasticity of cancellous bone samples were 137, 47.5, 23, and 12.4 MPa for the cellular bone samples and 6.5 MPa for the open-cellular bone samples. (note that trabecular bone in elder humans' mandible has an elastic modulus between 3.5 and 125.6 MPa[27]). Three identical specimens of each combination of cortical shell and cellular foam bone were prepared for implant stability measurements. The dimensions of each experimental specimen were 38 cm × 20 cm × 42 cm.

Implant stability measurement

For measuring ITV, pilot holes were drilled into each bone block specimen using a 3.2-mm drill, and then a self-tapping implant (3.75 mm × 13 mm; ICE, 3i Implant Innovation, Palm Beach, FL, USA) was inserted. The peak ITV (in N-cm) was measured three times for each specimen using a digital torque meter (TQ-8800, Lulton Electronic Enterprise, Taipei, Taiwan).

For ISQ after implant placement the Osstell resonance frequency analyzer (Osstell, Göteborg, Sweden) was used to measure implant stability. The L-shaped transducer (Type F1 L5, Osstell) was maintained perpendicular to the implant and was screwed by hand into the implant body as recommended by the manufacturer (Fig. 2). In order to standardize the procedure, all measurements were made with the transducer perpendicular to the jaw. The value of ISQ ranges from 1 to 100, where a high value (>60) indicates high implant stability, and vice versa. The RFA was repeated three times to obtain the ISQ data for each specimen.

To measure PTV, after connecting a 6-mm-long temporary abutment (implant temporary hexed cylinder, 3i Implant Innovation), the mobility of the implant was measured using the Periotest device (Siemens, Bensheim, Germany). The tip of the measurement device was placed perpendicular to the abutment at a distance of 2 mm, and it impacted the implant four times per second for 4 seconds (Fig. 3). The Perio-test^{TM} device measures the time that the rod remains in contact with the implant, with a shorter contact time indicating a more stable periodontium. The attached microcomputer converted the duration obtained from the measurement cycle to the PTV on a scale from –8 (very stable) to +50 (extremely unstable). The PTV was measured three times for each specimen.

Correlation and statistical analysis

The stability measures (ITV, PTV, and ISQ) of the designed combinations of cortical thickness and elastic modulus of trabecular bone were summarized as mean±SD (standard deviation) values, with differences between them evaluated using one-way analysis of variance (ANOVA). The nonlinear relation between stability measures and cortical thickness was modeled separately with quadric regression models for each type of trabecular bone. The same approach was applied for elastic modulus of trabecular bone and stratified by the different levels of cortical thickness. Three-dimensional graphs were used to present the relationship among stability, cortical thickness, and elastic modulus of trabecular bone. The quadratic model fitted to stability measures simultaneously included the cortical thickness, elastic modulus of trabecular bone, and their product term (if it was statistically significant). In the multiple regression models, the cortical thickness and elastic modulus of trabecular bone were centered around their respective means to ensure that the intercept of the models was interpretable, which is the predicted stability measure at the mean cortical thickness and the mean elastic modulus of trabecular bone. The goodness of fit for the regression models was quantified as the value of R^2. All statistical analyses were performed with SAS software (SAS v9.1.2, SAS Institute, Cary, NC, USA) with alpha set at 0.05.

Results

Table 1 lists the values of ITV, ISQ, and PTV for implants in the bone samples with various cortex thicknesses and strengths of trabecular bone. The ITV, ISQ, and PTV values all varied significantly with the thickness of cortical bone and elastic modulus of trabecular bone in one-way ANOVA ($p<0.005$). In general, bone with a thicker cortex had higher values of ITV and ISQ and a lower value of PTV. The correlations obtained in the second-order (i.e., quadratic) regression between cortex thickness and implant stability parameters (i.e., ITV, ISQ, and PTV) are shown in Fig. 4a, 4b, and 4c, respectively. The squared correlation coefficients were all higher than 0.9. The value of implant stability was increased exponentially for ITV but decreasingly for ISQ, and was reduced decreasingly for PTV as cortical bone was thicker (Fig. 4).

The trabecular bone with a higher elastic modulus exhibited appreciably higher ITV and ISQ and lower PTV (Table 1), except for the PTV and ISQ values in models with 47.5- and 137-MPa trabecular bone. The correlations obtained in the second-order regression between the elastic modulus of trabecular bone and the implant stability parameters (i.e., ITV, ISQ, and PTV) are shown in Fig. 5a, 5b, and 5c, respectively. The R^2 values were all higher than 0.9 for ISQ, and were 0.74–0.99 for PTV and ITV. The ITV increased linearly with the elastic modulus of trabecular bone (Fig. 5). However, the variations in PTV and ISQ with the elastic modulus of trabecular bone were higher when the elastic modulus was lower (Fig. 5).

The combined effects of cortex thickness and elastic modulus of trabecular bone on implant stabilities were modeled as second-order correlation equations (Fig. 6). In the figure, ET indicates the elastic modulus of trabecular bone (in MPa), TC represents the thickness of the cortex (in mm), and ET' and TC' are those two variables with their means subtracted (i.e., $ET'=ET - ET_{mean}$ and $TC'=TC - TC_{mean}$). The squared correlation coefficients between these two variables were 0.935 for ITV, 0.891 for ISQ, and 0.756 for PTV.

Discussion

Recent studies have examined how the primary stability of an implant is related to bone quality and quantity. Many of these studies have used the Lekholm and Zarb classification[19] to discriminate the bone quality[16,21] because this classification is easy and inexpensive to use. However, this classification only provides a rough discrimination of bone quality. It is very important to carefully consider the bone quality when planning treatments of immediate-loading implants, and therefore a more specific classification related to primary implant stability is needed. Using artificial bone is one option for investigating how the primary implant stability varies with the cortical thickness and the strength of trabecular bone. Unlike previous studies [14,28] using solid rigid foam to represent trabecular bone, the samples of trabecular bone in the present study were all cellular rigid foam, whose architecture is similar to that of trabecular bone; this approach might therefore provide more accurate results. For the biomechanical experiments, the cellular foam bone specimen has been reported a similar stress-strain curve to that of human trabecular bone[29], and also is a suitable biomechanical analogue to the human bone, especially in the screw thread–bone interface[30]. Therefore, the cellular form bone specimen has been suitably used in the pre-clinical testing of implants[28,31].

The effects of bone quality and quantity on ISQ and PTV have been widely discussed[16,21,32,33]. ISQ and PTV are obtained using noninvasive techniques and are easy to use clinically, which makes them favorable for dentists to determine the primary implant stability after implantation. The application of second-order regression in the present study revealed that both ISQ and PTV measurement techniques showed strong relationships with cortical bone thickness (R^2>0.92) and the elastic modulus of trabecular bone (R^2>0.9 for ISQ and R^2>0.7 in PTV). These results suggest that the initial stabilities of an implant as quantified by ISQ and PTV are influenced by the thickness of the cortical shell and the strength of trabecular bone. Increasing the cortical bone thickness increases the value of ISQ, which is in accordance with results obtained using cadavers, animals and computer models[10,32,34,35]. For example, Miyamoto et al.[9] found a significant correlation between ISQ and the thickness of the cortical bone. Because the cortex shell has a much higher elastic modulus (16.7 GPa) than all the trabecular bone specimens, making thin cortical bone (1 or 2-mm thick) thicker by bone augmentation techniques[36] could provide superior holding capacity for an implant at the time of installation.

Stronger trabecular bone also had a higher value of ISQ, which might increase the bone anchorage in nonosseointegrated BIC. Nkenke et al.[37] found that the ISQ measured in cadaver jaw bone was correlated with nonosseointegrated BIC of the oral aspect of the specimens, although the correlation was week. However, caution is necessary when using BIC to ascertain how implant stability is related to ISQ, because some studies have found no correlation between the progressive osseointegration of BICs and ISQ values[34,38]. Confirming the effectiveness of using RFA to predict the osseointegration level of an implant might require further scientific investigations. In addition, thickening the cortical bone and strengthening trabecular bone could reduce the value of PTV. This is consistent with Alsaadi et al.[21] finding in a clinical study that bone quality is related to PTV according to the Lekholm and Zarb index[19]. An increased primary implant stability may provide a good environment for osseointegration.

In the present study, ITV was correlated with the cortical bone thickness and the strength of trabecular bone. These results are in agreement with Trisi et al.[33] finding that bone strength was significantly correlated with ITV. An enhancement of ITV has been considered to be advantageous in improving the primary stability[9] and reducing micromotion between the implant and bone[33]. Such decreased micromotion might help to achieve a better osseointegration for immediately loaded implant and reduce the risk of failure of immediately loaded implant[4], and hence provide a favorable clinical result. Therefore, it appears to be highly desirable to determine the overall bone quality and quantity from the cortical bone thickness and the strength of trabecular bone at the time of implant surgery especially for immediately loading treatment. Using preoperative dental cone-beam CT in the clinic to objectively assess bone quality and quantity may be useful for predicting the primary implant stability before implant placement.

Osteoporosis is categorized into Types I and II. Type I osteoporosis most often occurs in women aged 50–75 years due to a sudden decrease in sex hormones, whereas Type II osteoporosis is closely associated with aged or senile bone. Due to the high success rate of implants more and more elderly people are willing to accept implant therapy for edentulous restoration. However, osteoporosis changes the characteristics of both cortical bone and cancellous bone, with cortical bone possibly becoming thinner and both the morphologic and mechanical properties of cancellous bone possibly changing[39,40]. Osteoporotic bone has an open-cellular structure that is much weaker than the normal cellular structure of normal cancellous bone[41]. Therefore, the presence of osteoporotic bone might influence the implant stability. In this study, ITV, PTV, and ISQ were significantly lower in osteoporotic bone. For thin cortex (1-mm thick), the differences between the models with and without osteoporotic bone were greater for ITV and PTV (by up to twofold) than for ISQ. This suggests that ITV and PTV are more suitable for diagnosing the primary implant stability, especially in patients with low-strength and osteoporotic trabecular bone. However, based on the limited information available in the literature[23,24], there is no absolute contraindication for implants in osteoporotic bone; even so, the diagnosis of primary implant stability might still be important to improve the osseointegration of an implant with osteoporotic bone[41].

Conclusions

The present study has revealed the relationships between the clinical use of ISQ, PTV, and RTV values and the cortical bone thickness and/or strength of trabecular bone. Even though this study employed artificial bone models that mimicked the advanced cellular structure of bone, real bone is a living tissue and hence there may be other biological factors that influence the initial stability of an implant. Therefore, further clinical studies are needed to elucidate the biomechanical mechanisms underlying how primary implant stability is affected by bone quality and quantity. Within the limitations of the current study, the following conclusions can be drawn:

1. Second-order regression equations for the correlation of cortical bone thicknesses with ITV, ISQ, and PTV had a high squared correlation coefficient (R^2>0.9). In thicker cortical bone the implant stability was raised exponentially for ITV but was increased decreasingly for PTV and ISQ.
2. The squared correlation coefficients for the correlation between the strength of trabecular bone and the values of ISQ, PTV, and RTV varied from 0.74 to 0.99. ITV increased linearly with the strength of trabecular bone, but the implant stability was decreasingly increased on PTV and ISQ as the strength of trabecular bone rose.
3. The use of ITV and PTV seems appropriate for assessing the primary stability of an implant in osteoporotic bone with a thin cortex.

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Figures Legends

Fig. 1. (a) The sawbone specimens with cortex thicknesses of 0, 1, 2, and 3 mm, and 137-, 47.5-, 23-, 12.4-, and 6.5-MPa trabecular bone. (b) Close-up images showing the differing structures of closed-cell rigid (left) representing various strength but normal trabecular bone, and open-cell rigid (right) specimens mimicking osteoporotic bone.

Fig. 2. L-shaped transducer set up as recommended by the Osstell manufacturer for making measurements after the bone model was fixed in the jig.

Fig. 3. PTV values were acquired after the rod of the Periotest device touched the abutment.

Fig. 4. Second-order regressions and squared correlation coefficients of ITV, ISQ, and PTV with the thickness of cortical bone.

Fig. 5. Second-order regressions and squared correlation coefficients of ITV, ISQ, and PTV with the elastic modulus of trabecular bone.

Fig. 6. Three-dimensional distributions, and correlation equations and coefficients of ITV (a), ISQ (b) and PTV (c) for the cortex thickness and the elastic modulus of trabecular bone.

Table 1. Mean and SD values of ITV, ISQ, and PTV of implants in cortical bone with four thicknesses and trabecular bone with five elastic moduli.

ITV (N-cm)

Thickness of artificial cortex (mm)	Elasticities of artificial cancellous bone specimens (MPa), Mean (SD)					
	137	47.5	23	12.4	6.5	P†
0	17.8 (0.7)	13.5 (2.2)	11.3 (0.4)	8.9 (0.1)	4.6 (0.1)	<0.0001
1	25.8 (4.1)	17.4 (2.4)	16.3 (2.1)	16.1 (2.7)	5.6 (0.6)	<0.0001
2	33.1 (3.9)	25.2 (4.6)	22.0 (5.0)	21.1 (2.6)	10.1 (1.4)	0.0003
3	72.0 (1.0)	53.0 (7.2)	47.7 (1.2)	42.3 (5.0)	35.0 (2.6)	<0.0001
P†	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	

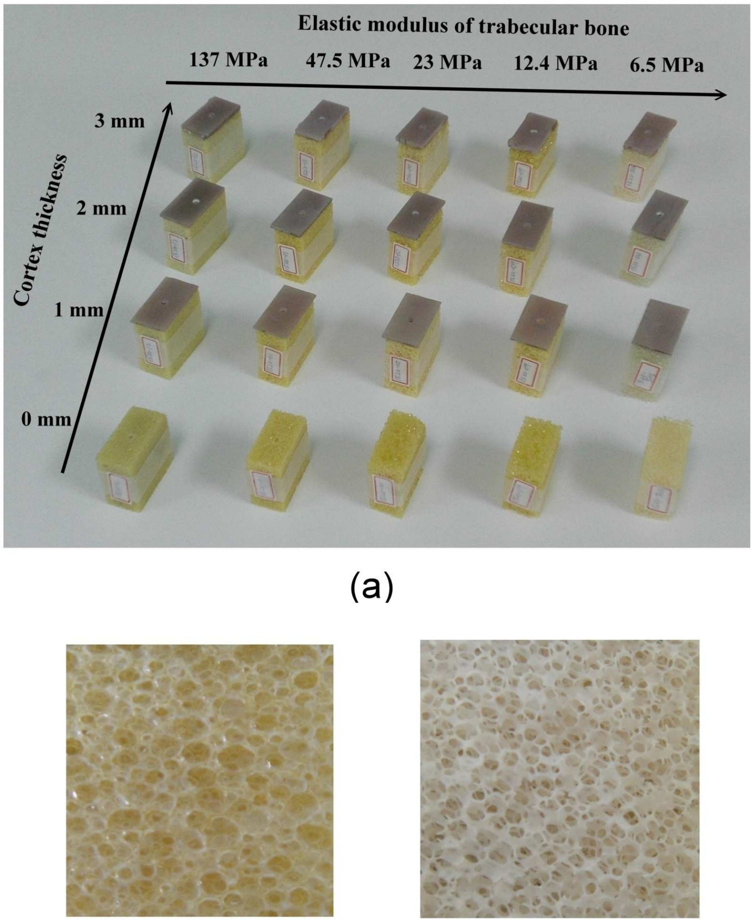
ISQ

Thickness of artificial cortex (mm)	Elasticities of artificial cancellous bone specimens (MPa), Mean (SD)					
	137	47.5	23	12.4	6.5	P†
0	66.0 (2.0)	60.3 (1.2)	63.3 (3.8)	55.7 (4.9)	48.3 (0.6)	0.0002
1	83.3 (3.1)	80.0 (3.6)	74.7 (1.5)	68.0 (2.6)	63.3 (2.5)	<0.0001
2	86.7 (2.3)	84.0 (1.7)	75.7 (7.6)	75.7 (4.5)	66.0 (1.7)	0.0010
3	87.7 (2.5)	85.0 (1.0)	80.5 (0.7)	75.0(1.0)	70.0 (1.7)	<0.0001
P†	<0.0001	<0.0001	0.0187	0.0005	<0.0001	

PTV

Thickness of artificial cortex (mm)	Elasticities of artificial cancellous bone specimens (MPa), Mean (SD)					
	137	47.5	23	12.4	6.5	P†
0	4.3 (1.5)	6.3 (1.5)	9.7 (3.1)	17.3 (3.2)	NA	0.0009
1	-0.3 (0.6)	0.7 (0.6)	4.3 (1.2)	8.0 (1.0)	24.7 (2.5)	<0.0001
2	-1.0 (0.0)	-0.3 (1.2)	2.0 (0.0)	6.3(0.6)	19.3 (1.5)	<0.0001
3	-3.7 (0.6)	-2.3 (0.6)	2.0 (1.0)	5.7 (1.2)	7.0 (1.7)	<0.0001
P†	<0.0001	<0.0001	0.0017	0.0002	<0.0001	

†One-way ANOVA



(a)

(b)

Fig. 1. (a) The sawbone specimens with cortex thicknesses of 0, 1, 2, and 3 mm, and 137-, 47.5-, 23-, 12.4-, and 6.5-MPa trabecular bone. (b) Close-up images showing the differing structures of closed-cell rigid (left) representing various strength but normal trabecular bone, and open-cell rigid (right) specimens mimicking osteoporotic bone.
177x177mm (300 x 300 DPI)

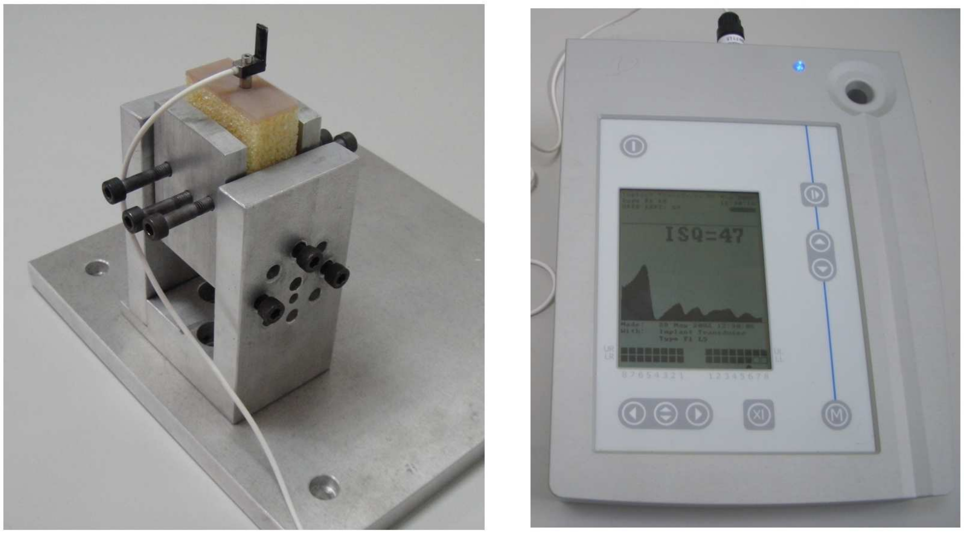


Fig. 2. L-shaped transducer set up as recommended by the Osstell manufacturer for making measurements after the bone model was fixed in the jig.
140x82mm (300 x 300 DPI)

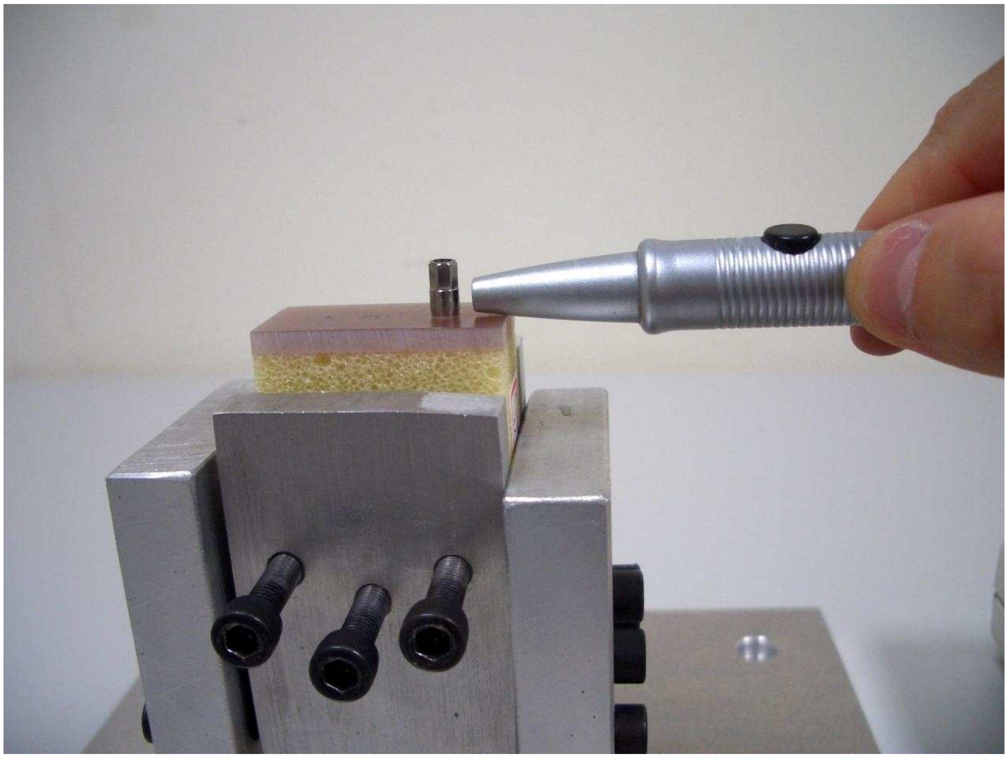
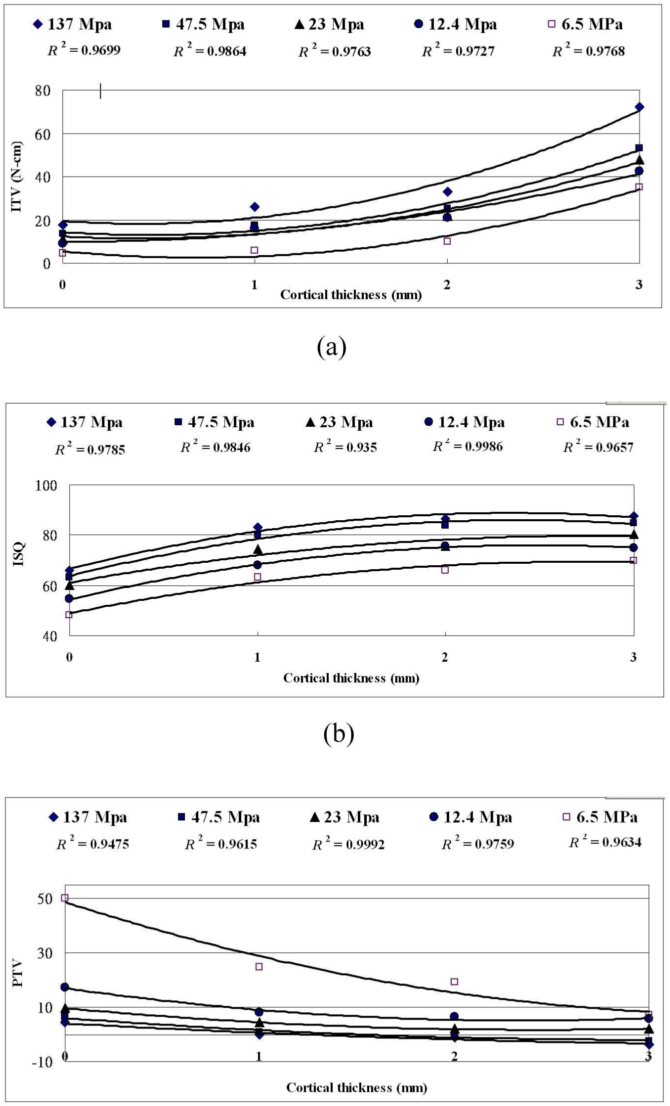


Fig. 3. PTV values were acquired after the rod of the Periotest device touched the abutment.
108x81mm (300 x 300 DPI)

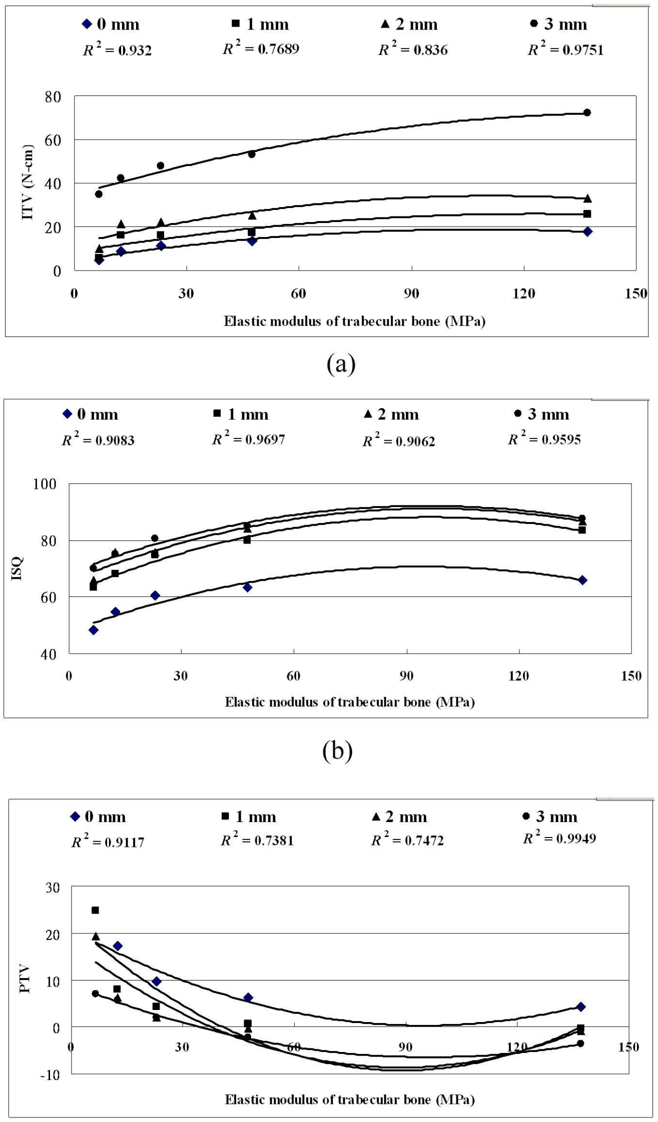


(a)

(b)

(c)

Fig. 4. Second-order regressions and squared correlation coefficients of ITV, ISQ, and PTV with the thickness of cortical bone.
124x205mm (300 x 300 DPI)

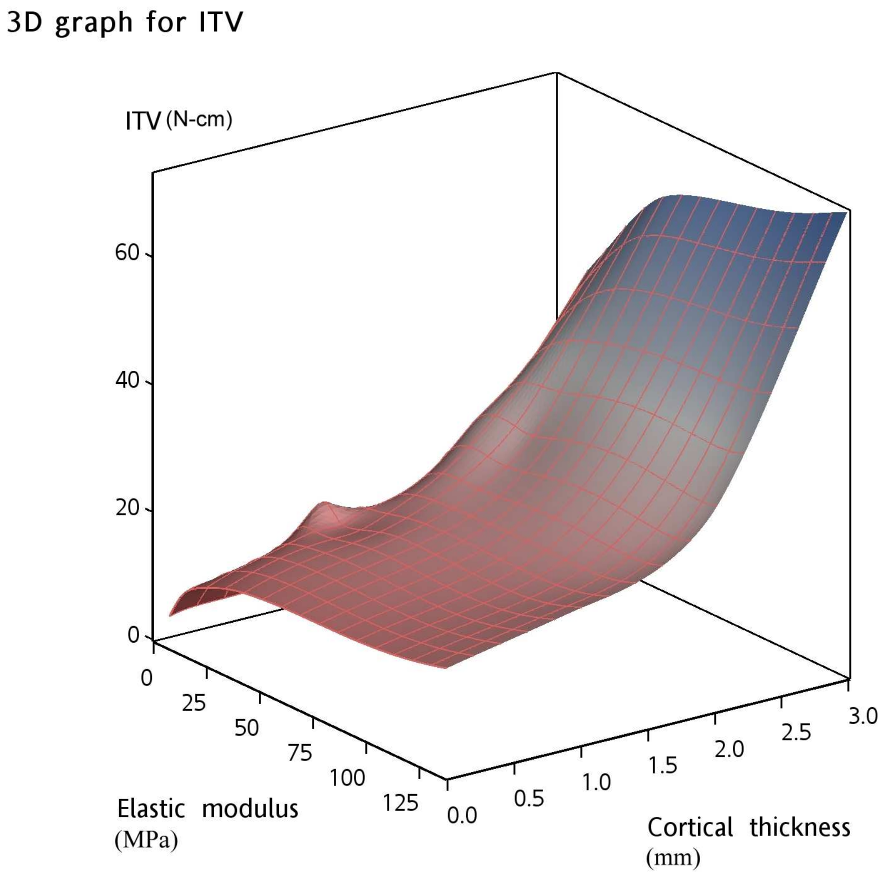


(a)

(b)

(c)

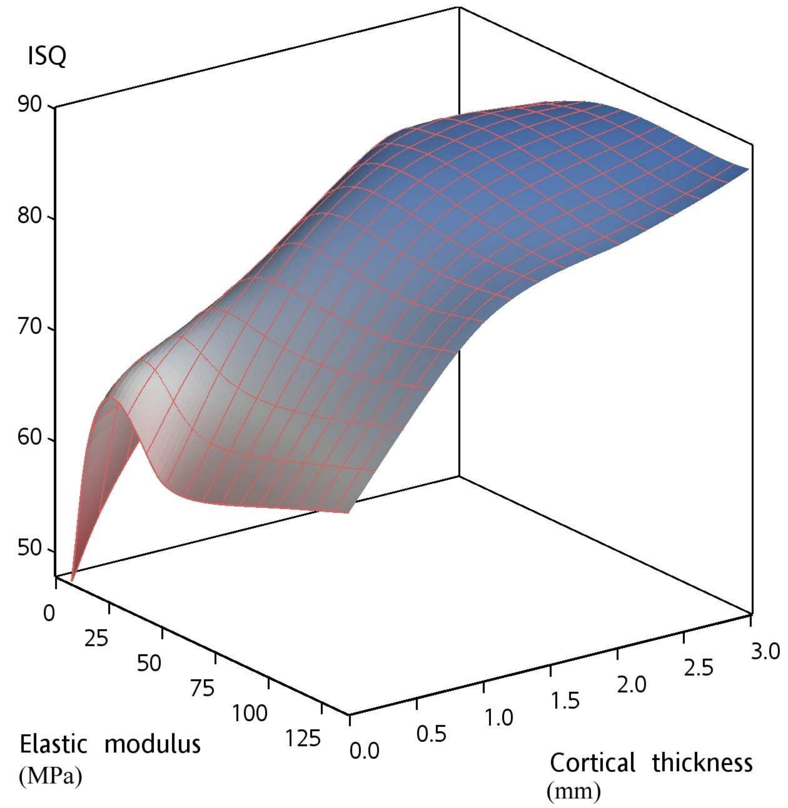
Fig. 5. Second-order regressions and squared correlation coefficients of ITV, ISQ, and PTV with the elastic modulus of trabecular bone.
123x210mm (300 x 300 DPI)



$$\mathbf{ITV = 21.225 + 0.230(ET') - 0.001(ET') + 12.239(TC') + 5.675(TC') + 0.053\,(ET'{*}TC');\ \ R^2 = 0.935}$$

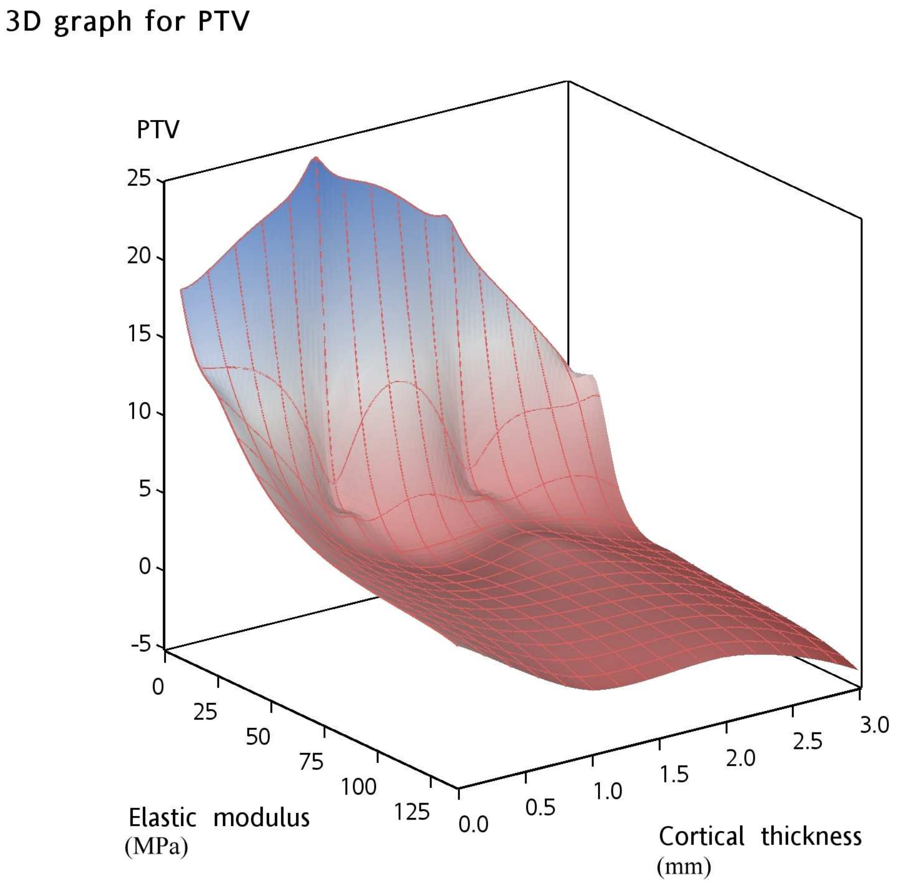
Fig. 6a

3D graph for ISQ



$$\mathbf{ISQ = 82.344 + 0.259(ET') - 0.003(ET')^2 + 6.588(TC') - 3.321(TC')^2;}$$
$$\boldsymbol{R^2=0.891}$$

Fig. 6b



$$\mathbf{PTV = -0.134 - 0.261(ET') - 0.003(ET')^2 - 3.097(TC');\ R^2 = 0.756}$$

Fig. 6. Three-dimensional distributions, and correlation equations and coefficients of ITV (a), ISQ (b) and PTV (c) for the cortex thickness and the elastic modulus of trabecular bone.