

# BONE QUALITY TESTING DURING DENTAL IMPLANT SURGERY

## *A Novel Device for Intraoperative Compressive Testing of Alveolar Bone*

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Abstract: Based on theoretical considerations, a mathematical equation was set up describing a correlation between density and mechanical properties of both, cortical and trabecular bone. Simulating the clinical situation of dental implant placement, finite element analysis was applied to test the validity of compressive testing of alveolar bone following implant site preparation. As a final step, a loading device was constructed accordingly and tested in human cadaver bone.

## 1 INTRODUCTION

Precise evaluation of alveolar bone quality is a prerequisite for successful implant therapy as dental implants are subject to masticatory loads of varying magnitude (Brunski, 1988). The type and architecture of bone are known to influence its load bearing capacity, and it has been shown that implants placed in poor quality bone have higher failure rates (Norton and Gamble, 2001). In clinical reality, bone quality does affect treatment planning and the choice of loading protocols for a specific patient.

This topic has been addressed by numerous authors and various techniques for evaluating bone quality have been described including preoperative radiographs, subjective hand feeling during drilling (Alsaadi, 2007; Trisi, 1999; Shapurian, 2006), implant insertion torque (Beer, 2003; Friberg, 1999a; Johansson, 2004), different forms of computed tomography (Aranyarachkul, 2005; Ikumi, 2005; Lagravere, 2006; Lindh, 1996) as well as measurement systems for the determination of

primary implant stability (Friberg, 1999b; Nkenke, 2003; Al-Nawas, 2006) such as the Periotest<sup>®</sup> (Medizintechnik Gulden, Modautal, Germany) and Osstell<sup>®</sup> (Osstell AB, Gothenburg, Sweden) device (Meredith, 1998; Schulte, 1992; Aparicio, 2006).

However, a recent literature review pointed out that a single objective evaluation method for bone quality is not available so far and that there is only sparse evidence for the efficacy of clinical methods to assess jawbone tissue prior to and during endosseous dental implant placement (Ribeiro-Rotta, 2007).

As compressive testing of human bone specimens has been successfully used in experimental research (Giesen, 2003; Giesen, 2004), it was planned to develop a system capable of conducting compressive tests on human alveolar bone during dental implant surgery (Figure 1).

Therefore, the purpose of this study was to design a method for the non-destructive determination of bone quality following implant site preparation. Using mathematical considerations and finite element analyses it has been clarified which

mechanical parameters have to be determined in order to obtain information on the elastic properties of bone at a specific site. Based on these findings, a clinically applicable device for bone quality testing was fabricated and used for preliminary testing in human cadaver bone.

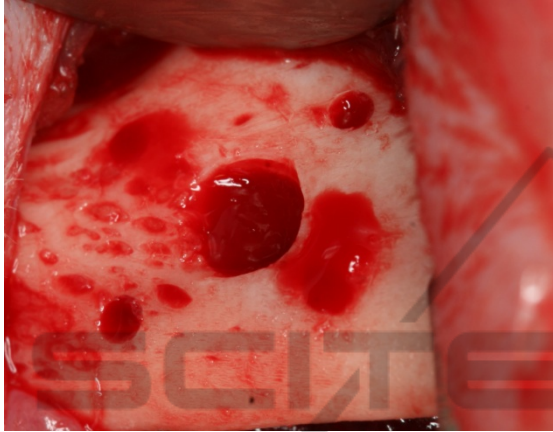


Figure 1: Clinical situation during dental implant surgery after preparation of an implant site using a series of twist drills. Note: Areas of decortication surrounding the implant site provide blood supply for local bone augmentation in this case.

## 2 STUDY PARTS AND FINDINGS

### 2.1 Theoretical Considerations

Given the non-homogeneous structure of both cortical and trabecular bone comprising hard tissue and bone marrow, volumetric bone mineral density  $vBMD = \frac{m_b}{V_b}$  ( $m_b$ : bone mass,  $V_b$ : bone volume) appears to be inadequate for describing bone. Apparent bone mineral density  $aBMD = \frac{V_b}{V} vBMD$  ( $V$ : total volume with bone mass and marrow) which takes marrow space into account and relative bone mineral density  $rBMD = \frac{aBMD}{vBMD}$  appear to be more appropriate.

For biomechanical considerations, bone can be described as a cellular structure or as a porous structure with a specific distribution of hollow spaces. In either situation,  $rBMD$  can be described as a function of geometric parameters describing unit cells.

For an analytical model, the relative elastic modulus for cellular structures may be described as

$$\frac{E}{E_b} = b (rBMD)^n \quad (1)$$

with  $E$  standing for the apparent elastic modulus and  $b$  and  $n$  representing material characteristics.  $E$  can also be described as a function of apparent density  $aBMD$

$$E = b \frac{E_b}{(vBMD)^n} (aBMD)^n = \bar{b} (aBMD)^n. \quad (2)$$

In order to be able to reflect  $rBMD$  values ranging from 0 to 1, a unifying equation was set up (Winter, 2008)

$$\frac{E}{E_b} = \frac{(rBMD)^p}{(3 - 2 rBMD)^m} \quad (3)$$

where  $p$  and  $m$  reflect material parameters. With the given equation it was possible to approximate values for trabecular bone reported by Yang and coworkers (Yang et al, 1999)

$$E = 528 E_t \phi^{1.92} \quad (4)$$

and

$$E = 1240 E_t \phi^{1.80} \quad (5)$$

with  $\phi \equiv rBMD$  being the fraction of bone and  $E_t = 10GPa$  being the tissue elastic modulus (Yang et al, 1999).

In Fig. 2 a comparison of Eq. (3) with Eq. (4) and Eq. (5) is shown over the whole range of the relative bone mineral density  $rBMD$ .

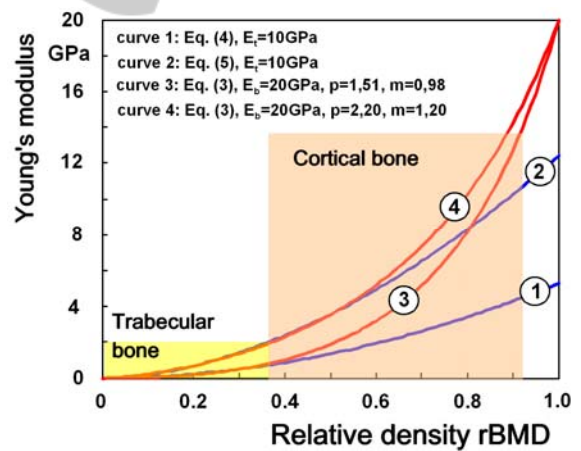


Figure 2: Comparison of Young's modulus over the whole range of relative bone mineral density. Bone quality can be characterized by the Young's modulus of bone or bone stiffness.

### 2.2 Design of a Device for Bone Quality Testing

A three-dimensional finite element model (MSC.Nastran®, MSC Software Partner Solutions, Marburg, Germany) representing a 25mm long

segment of a human mandible with an implant socket (diameter: 3.5 mm; length: 11mm) was generated (Figure 3). A peripheral layer (2mm thickness) and a central layer were created to model bone using tetrahedral elements. Bone was considered as an isotropic material with an elastic modulus of 20GPa in the cortical area and values of either 1GPa or 3GPa for trabecular bone. Poisson's ratio was set to 0.3 for both, cortical and trabecular bone and the free boundaries (anterior and posterior segment borders) were fixed. A loading device 3.5mm in diameter was positioned in the trabecular part of the implant socket and expanded by applying thermal expansion until a diameter of 3.510 mm was reached while the resulting pressure values  $p_1$  were recorded and used to calculate an elastic modulus  $E_1$  applying the equation

$$E_1 = p_1 \frac{E_0}{p_0} \quad (6)$$

with  $E_0$  and  $p_0$  standing for the calibration of the device.

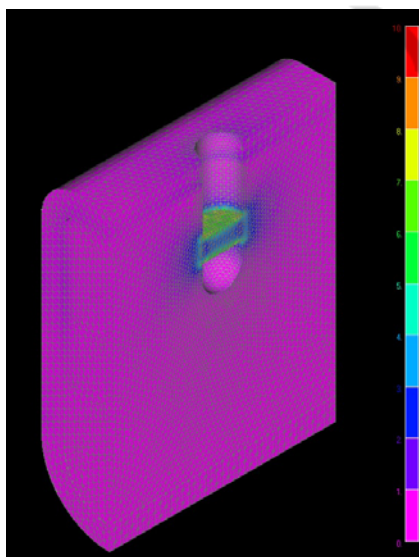


Figure 3: Finite element model used for validating intraoperative compressive testing for the objective classification of alveolar bone quality (scale: MPa). A loading device was placed in a readily prepared implant socket and the diameter of the device expanded. The stress levels measured were used to calculate bone's elastic modulus in this area.

The values obtained from the simulation yielded 940MPa and 955MPa for two different finite elements. Depending on the element considered, maximum deviations of 6% between pre-set values for the elastic modulus of bone and values derived from the simulation were found.

### 2.3 Fabrication of a Bone Quality Testing Device

An apparatus was constructed based on a metal cylinder with a diameter of 3.50 mm which was split into six segments. The cylinder could be expanded gradually while the actual force needed was recorded (Figure 4, Figure 5). This sensor could be placed into sockets prepared for the placement of cylindrically shaped dental implants and the diameter increased to 3.52mm and 3.57mm for measurements in the cortical and trabecular part of the osteotomy.



Figure 4: Total view of the bone quality testing device which is hand-held, motor driven and suitable for intraoral measurements.

### 2.4 In vitro Testing in Human Cadaver Bone

Segments of embalmed human mandibles and maxillas were obtained from the Institute of Anatomy, University of Erlangen-Nuremberg and subject to cone beam computed tomography (CBCT) scans (3D Accuitomo, J.Morita Europe GmbH, Dietzenbach, Germany). The sites for implant placement (number of sites: 110) as determined by CBCT were classified according to the region in the oral cavity (Maxilla / Mandible; Anterior / Posterior).

Table 1: Mean values and standard deviations for all measurements conducted in human cadaver bone.

	Drilling resistance	Bone quality testing device - cortical bone	Bone quality testing device - trabecular bone	Implant insertion torque	Resonance frequency analysis
Maxilla anterior	2.83 (0.72)	21.08 (8.68)	14.33 (6.87)	16.68 (11.66)	63.75 (12.99)
Maxilla posterior	2.85 (0.80)	14.01 (7.19)	14.70 (8.37)	9.33 (5.31)	64.92 (11.23)
Mandible anterior	1.34 (0.70)	34.65 (18.39)	30.55 (26.71)	29.72 (13.27)	75.39 (6.31)
Mandible posterior	1.60 (0.72)	43.66 (36.45)	21.21 (20.63)	30.53 (12.18)	78.46 (6.21)

Table 2: Pearson correlation coefficients for all combinations of measurements conducted in human cadaver bone.

	Drilling resistance	Bone quality testing device - cortical bone	Bone quality testing device - trabecular bone	Implant insertion torque	Resonance frequency analysis
Drilling resistance	1.0000	-0.4384	-0.3474	-0.6940	-0.4740
Bone quality testing device - cortical bone		1.0000	0.1712	0.4672	0.3321
Bone quality testing device - trabecular bone			1.0000	0.0621	0.1090
Implant insertion torque				1.0000	0.4619
Resonance frequency analysis					1.0000

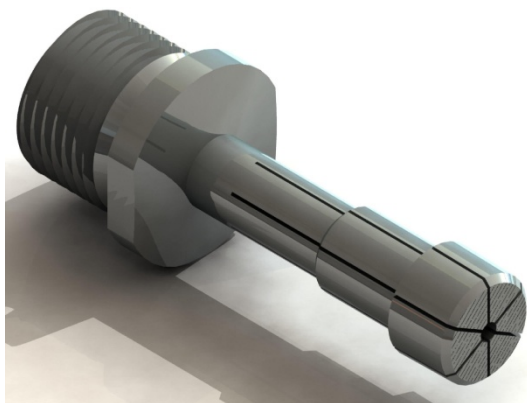


Figure 5: Sensing element of the bone quality testing device consisting of a cylinder which is split into six segments. The diameter of the cylinder can be increased and the forces needed are recorded.

A socket 3.5mm in diameter and 11mm in length was prepared for the placement of a screw-shaped cylindrical implant with a diameter of 4.1mm and 10mm bone sink depth (Straumann Standard Plus Implant; Institut Straumann AG, Basel, Switzerland)

in each site. The implant position was marked with a round burr and a set of twist drills 2.2mm, 2.8mm and 3.5mm in diameter was used in combination with a surgical motor (KaVo INTRAsurg 1000; KaVo Dental GmbH, Biberach, Germany) to create standardized implant beds. During implant bed preparation, the surgeon subjectively rated bone quality according to the Lekholm and Zarb classification system (Lekholm and Zarb, 1985). Compressive testing using the bone quality testing device was conducted in the areas of cortical and trabecular bone (Figure 6). The sensor was opened to 3.57mm in the cortical area and 3.52mm in the trabecular area of each socket. The forces needed to open the sensor were recorded in N. Implants were then installed using the surgical motor (KaVo INTRAsurg 1000; KaVo Dental GmbH, Biberach, Germany) measuring the maximum torque needed to insert the implants. Primary implant stability was determined by means of resonance frequency measurements (Osstell mentor, Osstell AB, Gothenburg, Sweden). For statistical analysis, Pearson correlation coefficients were calculated for all combinations of parameters.



Figure 6: Application of the bone quality testing device in a polyurethane foam model. Following implant site preparation, the sensing element is inserted in the osteotomy and opened gradually both in the cervical and apical part of the socket while the force needed for opening the sensor is measured.

The mean values and standard deviations for all measurements conducted are given in Table 1. Consistent with clinical knowledge, for all parameters greater values were recorded in the mandible as compared to the maxilla. Good correlations between the different measuring techniques were found.

### 3 DISCUSSION

It has been shown that the newly designed device can be used for the objective classification of human alveolar bone based on intraoperative compressive testing. The values obtained are consistent with already established measurement techniques either evaluating bone quality or primary implant stability. The major advantage of the system proposed is that it can be applied independent from any specific implant system thereby allowing for objective comparisons. As the implants have not yet been installed when the bone quality testing device is applied, the surgeon still has the choice to modify the treatment plan e.g. by selecting a tapered instead of a parallel walled implant in order to achieve greater primary stability. Based on the values obtained from the bone quality testing device, a decision can also be made with more confidence as to when a specific implant can be loaded with a certain type of superstructure. Following preclinical testing in animals, further prospective clinical trials are needed for establishing and verifying the diagnostic value of the bone quality testing device. The ultimate goal of the development should be to

establish threshold values on when a dental implant can be loaded immediately.

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