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ORIGINAL ARTICLE

Visualization of osseointegration of maxilla and mandible dental implants

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Abstract

Purpose We present a new, hybrid visualization method that can assist in assessing the degree of osseointegration of dental implants.

Method The method is based on radiographic imaging, three-dimensional (3-D) volume reconstruction, and color coding of bone density. It provides both a 3-D image of the titanium implant and the implant site, and a two-dimensional (2-D) profile of the lingual and buccal sides of the implant, exposing possible weaknesses in the supporting bone structure. The visualization procedure described here consists of 2-D cross-sectional CT imaging, 3-D gradient-based hardware-accelerated volume rendering using 3-D texture mapping, implant site extraction using 3-D selection of a 2-D cross-sectional, tri-linearly interpolated 2-D image, computation of a bone density profile and line integral along the implant, and 3-D hybrid rendering of the implant site and the derived bone density information in its anatomical context. This method has been demonstrated to be successful in enabling the mapping of information derived from virtual bone density measurements onto a geometric object, thus providing the necessary information to relate other information from mechanical testing or simulations to the respective site.

Results A high-resolution scan of a cadaver was used as a reference data set. The hybrid view, a combination of 2-D density profile and 3-D color-coded density rendering, turned out to be very intuitive and easy to interpret. The 2-D view was also useful for relating standard 2-D X-ray imaging with enhanced 3-D imaging of bone density. On top of this, our image-based method was used for cross-validation of a mechanical testing method. It turned out that the results from mechanical testing of osseointegration were very well correlated with the results from our image-based 2-D and 3-D methods.

Conclusions Since these two methods work in completely different ways (mechanical vs. radiographic) and the results came out are the same, the results provide evidence that both methods for assessing the degree and location of osseointegration are valid. Further studies using additional scans on living subjects will be conducted to provide additional evidence. Cost-efficient X-ray imaging can be used to replace the simulated implant-aligned 2-D X-ray views that were obtained from a 3-D scan.

Introduction

The lifetime and durability of dental implants depends primarily on the integration of the titanium socket in the bone. This process is called osseointegration. A long-term study has been conducted to analyze the effects of aging, mechanical stress, placement of the implant, and other impact factors. The information derived from virtual bone density measurements, in order to be related to information from other sources, must be visualized in the context of the anatomy. In the given cadaver study, a CT scan of the maxilla has been obtained, and two nearly adjacent implant sites with somewhat complementary properties have been selected as objects of study. The information from virtual bone density measurement, when visualized and compared to information from other sources, shows a good correlation with the results from mechanical testing and simulations.

X-rays and bone density

X-ray absorption is directly correlated to bone density. Therefore, a CT scan can be used to obtain the desired information

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Table 1 Hounsfield units of common substances

Substance	Hounsfield unit
Air	−1,000
Fat	−120
Water	0
Muscle	40
Bone	1,000

about the implant and its neighboring area. X-ray absorption is usually measured in Hounsfield units (Table 1).

Since the CT data file is stored in a 12-bit format (DICOM-3), the values are scaled and stored with a positive offset in a range from 0 to 4,095. For our purposes, we will use percentage values (0% is equivalent to air, and values approximating 100% are equivalent to bone). In reality, CT values for bone and tooth material are close together, whereas the implant appears as a denser material with very high X-ray absorption.

For visualization purposes, Hounsfield units are usually mapped to intensity values or colors. Since we use gradient-based transfer functions for color and opacity in our study, the absolute values of the Hounsfield units are less significant for a volume reconstruction. The visualization shows mainly gradient-based surfaces without the need to actually compute the surfaces in the form of polygonal patches. The method for direct volume rendering, which is an algorithm capable of displaying semi-transparent materials, is described in "Visualization methods overview".

The method is validated by comparing the results of the visualization with information from other sources: finite element simulation ("Comparison to computational simulation"), and mechanical stress testing ("Comparison to mechanical stress testing"). The hypothesis of this study is that bone density patterns are associated with success or failure of implant osseointegration, thereby confirming data generated by mechanical testing.

Implant materials and sites

For healthy teeth, the percussive energy produced by mastication processes is attenuated by the periodontal ligament at the bone–tooth interface. This ligament, however, is lost when the natural tooth is replaced with an implant for reasons such as disease or irreparable damage. The implant (Fig. 1) transmits the percussive forces directly into the bone at the material–bone interface. While other studies have been conducted to examine the mechanical damping behavior of dental implants, this study in conjunction with data from affiliate research and new scientific visualization technology will examine the effect on bone density due to mechanical energy dissipation from implant placement.

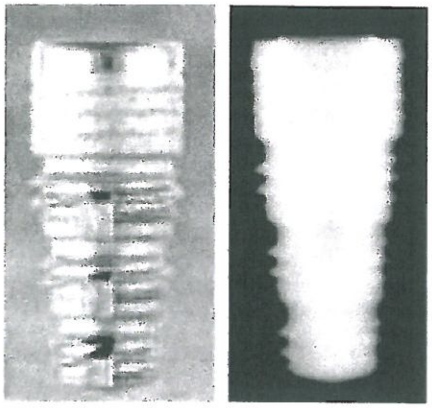


Fig. 1 Friadent Frialit-2 Synchro Dental Implant (*left* original, *right* CT)

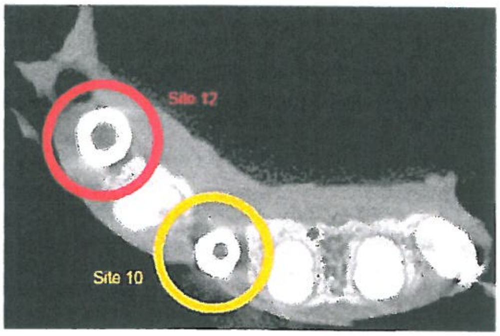


Fig. 2 Selected implant sites 10 and 12

In this study, two different dental implant sites (Fig. 2) were evaluated using a cross-sectional image-based method for the computation of bone density as a function of distance from the implant apex. This method is described in "Virtual 2-D bone density measurement".

Each cross-section is centered on the longitudinal axis of the implant reaching from the buccal to the lingual side. A sequence of density values along one side of the implant is called a profile ("Mapping of osseointegration data"). The average of such a density profile represents a line integral, which is supposed to be visualized together with the CT scan data in order to provide the necessary anatomical context.

The position of the implant is determined by three-dimensional (3-D) volume rendering (Fig. 3). Two 3-D locations are selected interactively to define the upper left and lower right corners of the cross-section, which is then written to a buffer for further analysis. These cross-sectional images, which are obtained from the CT scan using tri-linear interpolation, are then analyzed by an algorithm specifically designed for the computation of bone density values vertically strewn along the buccal and lingual sides of the implants.

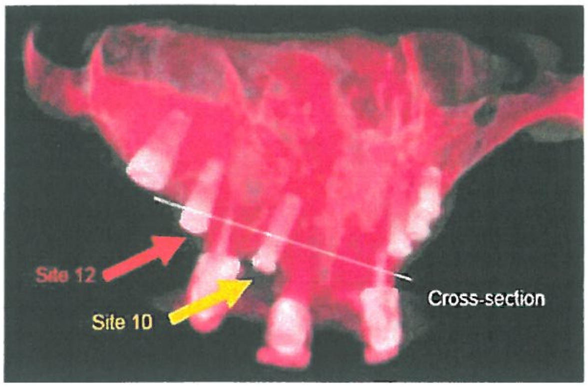


Fig. 3 3-D view of selected implant sites 10 and 12. The *white line* indicates the approximate location of the cross-section shown in Fig. 2

Previous studies and related work

Osseointegration is the permanent incorporation of an implant into bone. This direct and functional connection cannot be separated without fracture. Osseointegration is an important process, along with bone healing, which occurs after dental implants are placed and covered, after which the implants are uncovered and connected to an abutment to allow for mechanical loading [1]. A long-term study is currently underway to study the long-term durability of implants [2]. In our case, a patient with an available dental record dating back more than a decade was used in a cadaver study.

A sufficient amount of loading is needed to strengthen bone through bone formation around the wound site. If this requirement is not met or significantly exceeded, osteoclastic activity will commence and the bone subsequently removed from the site [3,4]. In therapeutic loading for dental implants, the implant design must replace the function of the periodontal ligament that is lost upon prosthetic placement by transmitting stress waves through the tissue near the natural level [5]. Also, the surrounding bone tissue must be stable to secure the implant prior to loading.

Given the importance of monitoring the development of bone that provides support, this paper suggests a virtual method of profiling the bone density gradient that surrounds the implant. We hypothesize that bone density patterns determined by density values collected from rendered images may indicate success or failure of implant osseointegration with the correlation and support of data obtained from mechanical testing.

One way to validate the hypothesis is the comparison of the visualization results to established methods of mechanical stress testing. One such method is based on measuring energy return through mechanical probing. A percussion instrument, such as a mechanical rod attached to an accelerometer, can be used for this purpose. Such an instrument is called a periometer. This instrument is capable of distinguishing the quality of the underlying bone upon implant placement. A rod is actuated to impact the sample, and data from the percussions are recorded as the raw energy return and displayed on a graph of normalized energy versus the time of each impact. The periometer was studied to distinguish the differences in primary stability of dental implants [5].

For the mechanical part of our study, energy return curves were generated using data collected by a periometer at the same implant sites where cross-sectional images were taken for the bone density profile. Both types of data were compared to determine the quality of the underlying bone material and possible defects in the osseointegration.

The computational part of our study required the implementation of visualization methods, which include two-dimensional (2-D) cross-sectional CT imaging, 3-D gradient-based [6], hardware-accelerated volume rendering using 3-D texture mapping [7–9], and implant site extraction using 3-D selection of a 2-D cross-sectional, tri-linearly interpolated 2-D image [10,11]. A new computational method for bone density profiles and line integrals along the dental implants was developed, and a 3-D hybrid visualization method has been implemented for rendering the implant site and the derived bone density information in their anatomical context.

By visually displaying the effects of variations in implant size, location of the implant site, bone density, and osseointegration, conclusions can be drawn for optimal placement and anchoring of dental implants, eventually leading to more stability, higher durability, and an increased lifetime of the implanted tooth.

For the given study, a 3-D CT scan was used to visualize the selected implants at sites 10 and 12 in the maxilla of the upper jaw of a human cadaver specimen. Individual data points, which corresponded to bone density values, were collected along designated lines vertically strewn along the buccal and lingual sides of the implants, as described in the next section.

Methods

This section describes the image-based methods used to measure bone density based on X-ray and CT scans, and the visualization methods used to display these data in the right context, i.e., directly on the implant site.

Virtual 2-D bone density measurement

In order to measure bone density in the proximity of the implant site, a 2-D cross-section was extracted from the volumetric grid using tri-linear interpolation. The cross-section intersects the longitudinal axis of the implant and reaches

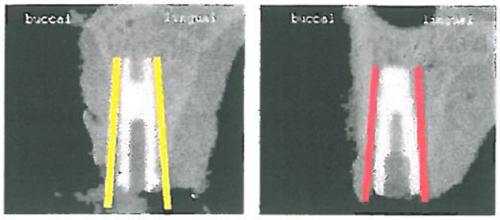


Fig. 4 Cross-sectional image of implant sites 10 and 12 derived from a volumetric CT scan. The *lines* designate the vertical line integral used to collect bone density values on the buccal and lingual sides. Bresenham's line algorithm was implemented for collecting the bone density information along a discretized line

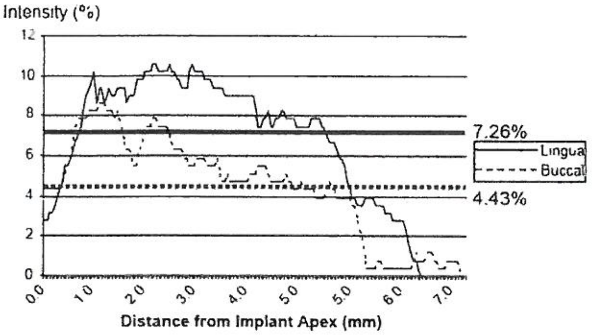


Fig. 5 Intensity for the lingual and buccal sides of implant site 10 (bone density)

from the buccal to the lingual side. By this way, a standardized coordinate system was defined for bone density measurements.

On either side of the implant, a straight line was drawn to collect density information near the implant (Fig. 4). The line originates at the same vertical coordinate as the apex of the implant and maintains a predefined horizontal distance to the implant. This line was then used to collect the data for the bone density profile and to compute the line integral, i.e., a single number that is characteristic for the bone density of a particular implant and side (buccal or lingual).

Implants come in different, standardized sizes. In order to normalize the line integral, only pixel values inside the bone and gums were included in the computation. Pixels with Hounsfield unit values characteristic for air or water (Table 1) were ignored. Also, if the line accidentally cut through the implant, those values would have been ignored as well. The sum of the pixel values was also divided by the number of pixels along the line in order to make the line integral independent from the size of the implant.

Typical profiles for implant sites 10 and 12 (buccal and lingual sides) are shown in Figs. 5 and 6. The horizontal axis represents the distance from the apex of the implant, and the vertical axis shows the intensity. The average, i.e., the value of the line integral, is shown as a horizontal line with a percentage value.

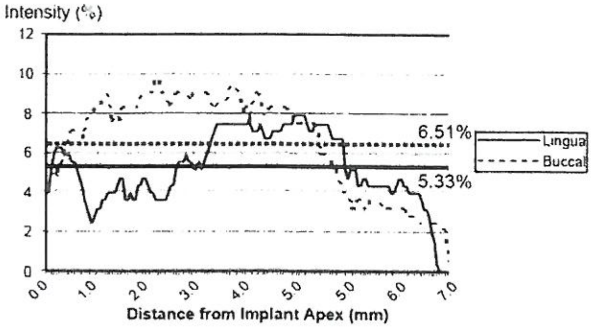


Fig. 6 Intensity for the lingual and buccal sides of implant site 12 (bone density)

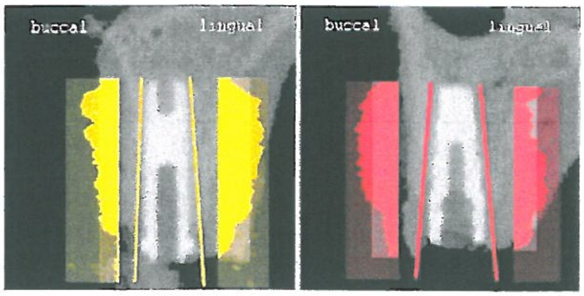
Note that in implant site 10, the lingual side appears to be stronger, whereas in implant site 12, the buccal side appears to be stronger. This could have been caused by various effects, including aging, placement of the implant, and mechanical stress.

Mapping of osseointegration data

Instead of presenting the data in a diagram, the density profiles can be visualized directly on the 2-D cross-section (Figs. 7–8). The orientation of the profiles has been rotated to reflect the mutual support of the implant from the bone on the buccal and lingual sides.

When shown in context, the profiles show the amount of horizontal support for each vertical position. The images clearly show that the support is usually better near the apex of the implant. The two examples also indicate that there may be differences in the buccal and lingual support of the implant. This will also be shown later in the mechanical tests ("Comparison to mechanical stress testing").

In addition to the density profiles, it was desirable to have a single characteristic number as an indicator of osseointegration for each site. The line integral as a normalized sum



Figs. 7–8 Bone density profiles for the lingual and buccal sides of implant sites 10 and 12 (with average shown as *lighter area*)

represents such a number. The line integral is computed for the buccal and lingual sides. It can be visualized together with the density profiles as a highlighted area on both sides of the implant. The width of the area is an indicator for the degree of osseointegration (Figs. 7–8).

The following observations were made from these visualizations. For both implant sites the bone density values followed a general trend of an initial rise, peak plateau, and fall as distance increased from implant apex (Figs. 7–8). Early rise and peak in bone density was generally seen within 3 mm from the implant apex. This range of increased bone density may be explained by the presence of a high-density layer of cortical bone at the dorsal bone–implant interface [5].

It is important to note the exception to this trend in the data collected for the lingual side of site 12 as shown in Figs. 7–8. Another important notable observation is the lack of prominent plateaus in the curves generated for the buccal and lingual sides of implant site 10 as shown in Figs. 7–8. These occurrences are discussed in "Comparison to mechanical stress testing" in conjunction with data obtained from a related mechanical study.

Following the peak plateaus of bone density for both implant sites 10 and 12, which correspond to the lateral incisor, and first bicuspid or premolar, respectively, the buccal regions generally displayed lower trends of decreasing bone density than the lingual sides. This incidence may be expected since the density of bone mass of the buccal cortex within the incisive and premolar region is known to be lower than the density of the corresponding lingual cortex [12].

Visualization methods overview

The bone density profiles as described in "Implant materials and sites" are mapped back to a 3-D volume and rendered together with the CT scan.

Alternatively, bone density information can also be shown directly in a volumetric rendering of the CT scan ("3-D volume visualization"). Gradient-based color and opacity transfer functions are employed to obtain a 3-D, translucent image of the maxilla, the embedded implants and teeth, and the density of the bone at each voxel. The color in these images indicates the density of the bone (green: low, amber: medium, red: high; Figs. 9, 10). Finally, a hybrid rendering mode is employed to show the 2-D bone density profiles for the buccal and the lingual side of an implant in their anatomical context. This mode is called hybrid visualization ("Hybrid visualization"; Fig. 11).

3-D volume visualization

An alternative method for visualizing bone density information is shown in Figs. 9 and 10. Here, a 3-D volume rendering shows the implant in its anatomical context. Teeth and

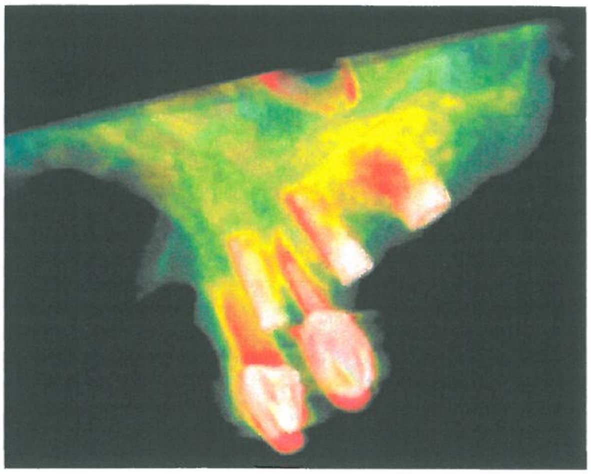


Fig. 9 Maxilla (CT scan), dental implants (*color* indicates bone density: *green* low, *amber* medium, *red* high)

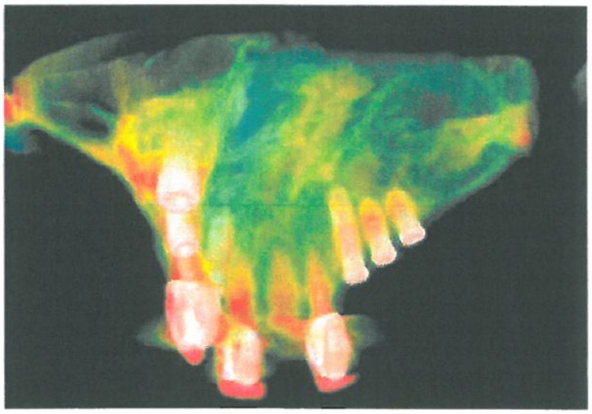


Fig. 10 Maxilla (CT scan), alternative view

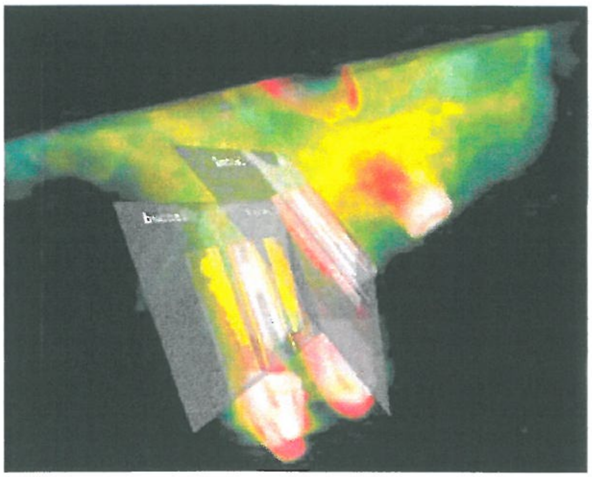


Fig. 11 Combined volume and cross-section rendering of bone density for implant sites 10 and 12

implants are shown in a neutral color (white), whereas the bone regions were color-coded to indicate areas of varying bone density. Green areas correspond to low density, amber indicates medium, and red indicates high density of the bone material. The color is a direct indicator for the degree of osseointegration of each implant site.

The size of the volumetric CT scan was 837 × 837 × 374 voxels stored as 16 bit data (0.5 GB). The direct volume rendering algorithm uses gradient-based transfer functions for color and opacity, and 3-D texture mapping for interactive display. The volume data were rendered in real-time at approximately 3–5 fps on a Dell PC with an Intel® Pentium® 4 CPU, 2.66 GHz, 1 GB RAM, and an ATI Radeon X1650 PCI Graphics Adapter with 512 MB video RAM running the Windows Vista Ultimate Operating System.

Hybrid visualization

In order to combine information from different sources (density profiles, anatomical data, and color-coded bone density), a hybrid visualization mode was introduced. In this mode the 2-D cross-sections extracted from the volume data set combined with the intensity profiles associated with the buccal and lingual sides of the implant and the value of the line integral as a highlighted area are superimposed onto the volumetric data set in their correct anatomical position. When rotating the data set, each implant can be inspected, and the corresponding data come into view.

This hybrid mode combines 3-D volume rendering, as described in "3-D volume visualization", with the 2-D cross-sectional data, as described in "Mapping of osseointegration data", to provide a comprehensive view of the degree of osseointegration for various implant sites.

Figure 11 shows a hybrid rendering for the selected implant sites 10 and 12.

Discussion

This section compares the results from the computational simulation to the results from mechanical stress testing and discusses typical findings.

Comparison to computational simulation

A finite element simulation has been conducted to determine the effects of horizontal and vertical stress on teeth [13]. While vertical stress (mostly from clenching) mainly results in stress near the base of the tooth, horizontal motion (mostly from chewing) results in stress that is routed through the roots into the surrounding bone material.

The visualization (Fig. 12) shows that depending on the position of the teeth the principal stress occurs either in the buccal or in the lingual side. Due to the natural position of the teeth, in the given simulation the stress seems to be concentrated more on the lingual side, which corresponds to the findings from implant site 10 in the measured bone density data (Figs. 7–8). For other positions, this may be different, as shown in implant site 12 (Figs. 7–8).

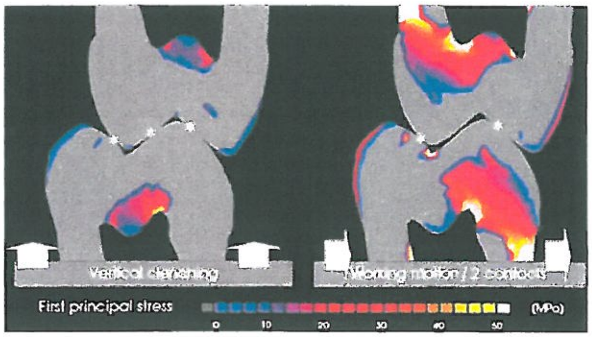


Fig. 12 Stress in teeth simulation [13] (reprinted with permission from Quintessence Publishing Co., Inc.)

Fig. 13 Percussion testing

Comparison to mechanical stress testing

A typical method for testing osseointegration is percussion testing (Fig. 13). In order to obtain quantitative data, a mechanical device called periometer has been used to further analyze the situation of horizontal stress. A periometer has a mechanical rod combined with an accelerometer to measure the energy return after percussion. The rod is actuated to impact the sample 16 times over a period of 4 s (Fig. 14). Data from ten of the percussions are recorded as the raw energy return and displayed on a graph of normalized energy versus the time of each impact.

Figures 15 and 16 show the normalized energy return curves for implant sites 10 and 12, respectively. The differences between implant sites 10 and 12 that were observed in the visualization are also evident in the mechanical data collected by the periometer.

The raw energy return data have been suggested to detect poor stability at the bone–implant interface as caused by defects or irregularities in the bone structure. These cases are evidenced by a variation from a uniform bell-shaped curve

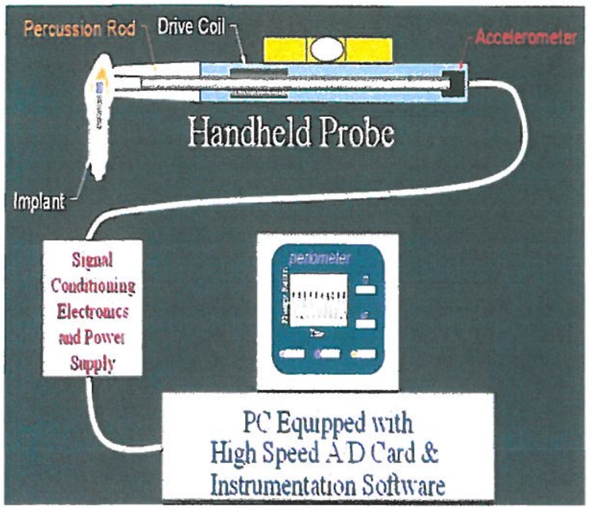


Fig. 14 Periometer system

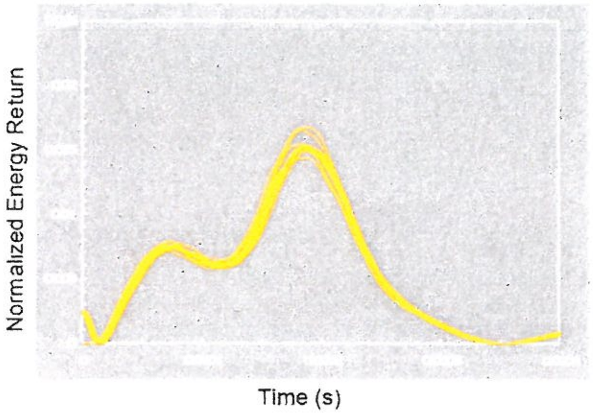


Fig. 15 The normalized energy return curve for implant site 10. The periometer produces measurements for the energy return at each time of impact

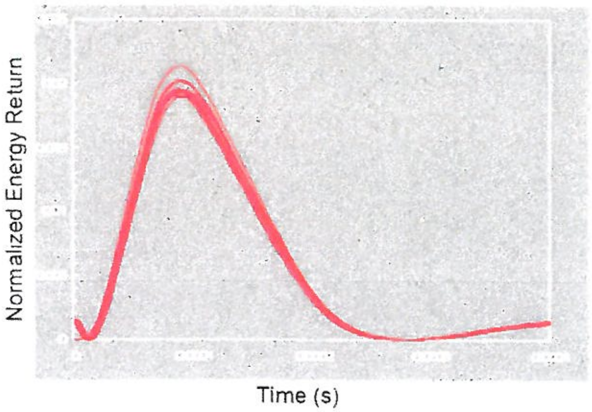


Fig. 16 The normalized energy return curve for implant site 12. The periometer produces measurements for energy return at each time of impact

displaying energy return versus time [5]. In the case of the bone density trend of implant site 10 lacking a prominent plateau, the associated energy return plot displays a fluctuation dip along the rise of the bell-shaped curve as shown in Fig. 15. Both the virtual and mechanical sets of data indicate possible loss or insufficient bone mass along the same region.

In the case of the bone density trend of implant site 12 displaying lower bone density values on the lingual side at the dorsal bone–implant interface where high-density values were expected, a slight variation from a uniform bell-shaped curve was observed in the associated energy return plot (Fig. 16). The lack of higher bone density values on the lingual side at the interface may be associated with the asymmetrical lean of the left side of the energy return curve produced by a steeper slope.

The irregular data trends produced for implant sites 10 and 12 are further supported by the observation of lower density materials used in a previous study that utilized the periometer having the tendency to have more fluctuations in the energy return curves [5].

Conclusions

We presented a method for virtual computation of bone density for dental implants. Small sample images for each implant were extracted from a 3-D CT scan. Bresenham's line algorithm was implemented to collect density values along a designated distance (mm) from the apex of the implant. The density profiles were then mapped onto the 2-D sample image and shown together with the line integral as a general measure for osseointegration.

In addition, a direct volume rendering method using gradient-based transfer functions for color and opacity was used to visualize the density of the bone material in the neighborhood of the implant.

Both visualization methods were combined in order to obtain a comprehensive view of osseointegration for each implant site.

The results from the virtual study were correlated with two other methods. One method was based on a finite element simulation of stress in teeth, while the other method was based on mechanical percussion testing (normalized energy return).

Overall, the results show a good correlation between the virtual study and the other two methods that were used for reference, confirming the initial hypothesis that a virtual method is suitable as an indicator for osseointegration.

From the data collected by virtual and mechanical testing, it was evident that the bone density profile of the implant is site-specific and/or determined by the extent to which bone develops around the implant. The results obtained by the present study may serve as a platform for the future examination of the process of bone healing and development in vivo. The mechanical testing may be conducted using the periometer, while one possible method of collecting bone density values may be the virtual procedure implemented for the present study.

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References

1. Gapski R, Wang H-L, Mascarenchas P, Lang NP (2003) Critical review of immediate implant loading. Clin Oral Implant Res 14:515
2. Vazquez L (2009) Osseointegration of dental implants inserted in non sterile operating conditions: a 12-year prospective evaluation of more than 9000 implants. In: Proceedings of the academy of osseointegration 2009 annual meeting: "A new wave in implant therapy", San Diego, 26–28 February 2009
3. Forwood MR, Turner CH (1995) Skeletal adaptations to mechanical usage: results from tibial loading studies in rats. Bone 17:1975
4. Robling AG, Duijevelaar KM, Geevers JV, Ohashi N, Turner CH (2001) Modulation of longitudinal and appositional bone growth in the rat ulna by applied mechanical force. Bone 29:105
5. VanSchoiack LR, Wu JC, Sheets CG, Earthman JC (2006) Effect of bone density on the damping behavior of dental implants: an in vitro method. Mater Sci Eng 26: 1307–1311
6. Kniss J, Kindlmann G, Hansen C (2001) Interactive volume rendering using multi-dimensional transfer functions and direct manipulation widgets. In: Proceedings of IEEE visualization 2001, pp 255–262
7. Dachille F, Kreeger K, Chen B, Bitter I, Kaufman A (1998) High-quality volume rendering using texture mapping hardware. In: SIGGRAPH eurographics graphics hardware workshop, pp 69–76
8. Westermann R, Ertl T (1998) Efficiently using graphics hardware in volume rendering applications. In: Computer graphics (SIGGRAPH '98), vol 32(4), pp 169–179
9. Meissner M, Guthe S, Strasser W (2001) Higher quality volume rendering on PC graphics hardware. Wilhelm Schickard Institute for Computer Science, Graphical-Interactive Systems (WSI/GRIS), University of Tuebingen
10. Meyer J, Gelder S, Kretschmer K, Silkenbauumer K, Hagen H (1997) Interactive visualization of hybrid medical data sets. In: Proceedings of the WSCG '97, vol 2. Pilsen, Czech Republic, pp 371–380
11. Sengupta R, Meyer J, Zhang Z (2004) Hybrid pipelining approach to image alignment for large-scale brain image data. In: 7th IASTED international conference on computers, graphics, and imaging (CGIM 2004), Kauai, Hawaii, pp 78–83
12. Wowern N (1975) Variations in bone mass and bone activity within the mandible. Calcif Tissue Int 21:397–404
13. Magne P, Belser U (2002) Rationalization of shape and related stress distribution in posterior teeth: a finite element study using nonlinear contact analysis. Int J Periodontics Restor Dent 22:425–433