Evaluation of Multiple Implant-Bone Parameters on Stress Characteristics in the Mandible Under Traumatic Loading Conditions

Author
Guan, Hong, van Staden, Rudi, Loo, Yew-Chaye, Johnson, Newell, Ivanovski, Saso, Meredith, Neil

Published
2010

Journal Title
The International Journal of Oral & Maxillofacial Implants

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The modern dental implant is a biocompatible titanium device surgically placed into the jaw bone to support a prosthetic tooth crown to replace missing teeth. Although dental implants exhibit excellent long-term retention rates (roughly 95% after 5 years), there are significantly more failures in areas where bone quality and density are low, resulting in poor patient outcomes. Most failures arise from poor clinical technique and inadequate understanding of the potentially damaging stress characteristics during implant placement and function.

Himmlova et al, Iplikcioğlu and Akça, and Pierrisnard et al have all recognized the fact that an implant’s dimensions influence the magnitude and distribution of stresses within the bone. It is commonly understood that increasing the implant diameter and/or length reduces the stresses within the bone.
Furthermore, based on clinical experience, practitioners appreciate the fact that if the bone is weak, then a larger-diameter implant is required. However, these decisions are based primarily on clinical judgment rather than being supported by any theoretical data. It is critical for practitioners to fully grasp the inter-relationships between various combinations of implant and bone parameters and the resulting stresses in the bone exerted by maximum masticatory forces under traumatic loading conditions.

Extensive research has been done on the stress distribution characteristics in bone surrounding implants. However, limited work has been done on the stress distribution in bone under various combinations of implant and bone parameters. Considering a wide range of masticatory forces, implant diameters and lengths, cortical bone thicknesses as well as material properties of cancellous and cortical bone, Guan et al demonstrated that:

1. An increase in implant length leads to a greater area of contact between the implant and bone, thereby reducing the magnitude of stresses;
2. An increase in the Young’s modulus of both cancellous and cortical bone and a decrease in the cortical thickness result in elevated stresses within both cancellous and cortical bone; and
3. The applied masticatory force has been demonstrated to be the most influential, in terms of differences between the minimum and maximum stress values, versus all other parameters.

As a logical extension, this study aimed to evaluate the inter-relationships between a total of five implant and bone parameters in terms of the von Mises stresses within the mandible. Note that only a traumatic loading condition was considered herein, because once the stresses created by maximum loading are determined, those under the minimum at an intermediate level can be readily obtained. Based on the stress distribution characteristics, various parameters will be ranked to reflect the most and the least influential parameter. For each parameter, this study also sought to predict bone fracturing status during functional loading. It is hoped that the findings of this study will help dental practitioners identify the stimulus state of the bone, hence providing the ability to predict the behavior of bone for all combinations of implant diameter and length with given cortical bone thickness, and material properties of cancellous and cortical bone, under various loading conditions.

METHODS AND MATERIALS

Two-Dimensional Representation of Implant and Bone System

A cross-sectional slice was taken from the mandible, as shown in Fig 1. The “arc length” of the mandible was comparable to the width and depth of the slice. When the slice was subjected to in-plane (x-y) masticatory forces (resulting from horizontal and vertical loading), it was restrained from deforming out of plane (in the z-axis). Therefore, it can be assumed that all the strains were confined in the z-axis. To accurately represent the mechanical behavior of the implant and bone, three-node triangular and four-node quadrilateral plane strain elements were therefore used for the construction of the finite element models.

Figure 2 shows a simplified symmetric mandible section and implant with the designated loading and restraint conditions. Also shown in Fig 2 are the detailed parameters considered in this study: the implant length (L) (7, 9, 11, 13, and 15 mm), the implant diameter (D) (3.5, 4.0, 4.5, and 5.5 mm), Young’s modulus of cancellous bone (E<sub>can</sub> = 1 to 14 GPa), Young’s modulus of cortical bone (E<sub>cor</sub> = 7 to 20 GPa), and the cortical bone thickness (T<sub>cor</sub> = 0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 2.0 mm).
and 2.1 mm). Based on commonly assumed ranges for Young's modulus of cancellous (Ecan = 0.08 to 7.93 GPa) and cortical bone (Ecor = 5.57 to 22.8 GPa), this study examined a wider range of Ecan (1 to 14 GPa) and Ecor (7 to 20 GPa), both at 1 GPa intervals (see Fig 2). The selection of such ranges was based on the understanding that, in some exceptional cases, Young's modulus of cancellous bone can reach 14 GPa when that of cortical bone is also at a high range. The Young's modulus of the implant was 105 GPa. The Poisson's ratios for cancellous bone, cortical bone, and the implant were assumed to be 0.3, 0.35, and 0.3, respectively.

The modeled implant was conical with 2 degrees of taper and had helical threads. For a particular finite element model with D = 4.5 mm, L = 11 mm, and Tcor = 1.2 mm, the total numbers of plane strain elements were 5,956 for cancellous bone, 1,094 for cortical bone, and 2,870 for the implant. The total number of nodal points in the entire model was 9,969.

Given the wide variety of abutment connection systems, the implant abutment and crown were omitted from the model, meaning that the masticatory force was transferred to the top of the implant. This resulted in a concentrated moment (M) acting on the implant top as a result of lateral transfer of the horizontal load (F_H). A traumatic loading condition was considered where F_H = 250 N, F_V = 500 N, and M = 1,625 Nmm, assuming the height of the crown is 6.5 mm. These loading magnitudes are commonly assumed in the literature. The cortical bone was constrained along the left and right faces of the cross section in the distal direction (see Fig 2), thus representing a realistic function of the mandible surrounding an implant.

As indicated in Fig 2, the von Mises stresses along the lines VV for cancellous bone and HH for cortical bone were measured for all possible parameter combinations. The relative locations of these lines are considered by clinicians to be critical for examining the stress levels and helping to understand the stimulus response of bone. Both lines VV and HH are dependent on the implant dimensions and Tcor. Because of the irregularity of the mesh, a straight line (VV) of nodes used for measuring stress was only approximated. The distance of VV from the thread tip was not a varying parameter affected by the implant diameter but was fixed at 0.2 mm (see Fig 2) in an attempt to capture the stresses at the most critical location.
Fifty Percent Osseointegration Between Implant and Bone

The interface surrounding an implant includes both blood and bone fragments. This interface is considered clinically ideal for osseointegration, although it is mechanically unfavorable. The stage after insertion and before complete osseointegration is critical for the surrounding bone because it exhibits the most distinct stress concentrations. After osseointegration is established, however, the lamina dura is formed and implant stability drastically increases.

Previous finite element studies assumed that immediately loaded implants are in direct contact with cancellous bone, without a blood interface. In a study by Natali et al., two formation stages of the lamina dura were modeled by setting Young’s moduli at 0.3 and 1.5 GPa, respectively. The formation of the lamina dura improved the stress distribution and represented a clinically favorable course of healing. A study by Berglundh et al. provided an overview of the various phases of blood and hard (bone) tissue formation during the bone healing stages at the implant-bone interface, sampled 2 hours after implant placement. The blood interface extended 0.13 mm into the thread chamber.

The percentage of bone-to-implant contact refers to the amount of mineralized tissue directly in contact with the implant surface and is based on histologic observations. Cancellous bone is composed of both mineralized tissue and bone marrow. Histologic analysis of osseointegrated implants has shown that, following osseointegration, the bone-to-implant contact is approximately 50%. This percentage was assumed in this study, and the voids between the implant and cancellous bone were modeled as blood, with Young’s modulus and Poisson’s ratio being 0.7 GPa and 0.3, respectively (Fig 2). On the other hand, cortical bone is composed almost exclusively of mineralized tissue with no intervening bone marrow. This is why cortical bone was modeled as 100% bone-to-implant contact.

**Linear Relationship Between Stress and Young’s Modulus**

Figure 3 shows the methodology for predicting the linear relationship between the von Mises stress and Young’s modulus Ecan (Ecor). The actual stress values at any specific point along either VV or HH were measured at the four corners representing the combinations of the minimum and maximum values of Ecan and Ecor. Between any two actual stress values when either Ecan or Ecor was constant, a linear relationship between the von Mises stress and Ecan (or Ecor) was predicted. This prediction was then extended to any combination of Ecan and Ecor, provided that one of them was constant. At the midpoint of line VV, the predicted stresses by the linear relationship were proven to be quite close to the actual ones in that the average ([predicted – actual]/actual) values are 5.7% and 4.3%, respectively, for Ecan and Ecor. Similar prediction errors were produced at the midpoint of line HH (4.9% and 6.5% for Ecan and Ecor, respectively). This confirmed the validity of the proposed linear relationship.

With the assumption of linear relationships between the stress and Ecan or Ecor, only the minimum and maximum values of Young’s modulus were considered for each type of bone instead of the initial data set of 14 values. Hence, the total number of analyses was 560 as a result of the number of variables being 4, 5, 7, 2, and 2 for D, L, Tcor, Ecan, and Ecor, respectively.

**RESULTS**

All analyses were carried out using Strand7 Finite Element Analysis System. A previous study evaluated the von Mises stress distribution in the bone when various combinations of parameters were considered. The present study advances on the previous research in the following ways: (1) it seeks to evaluate the inter-relationships between any single parameter and all other parameters; (2) it aims to rank all the parameters in terms of stress variations resulting from the minimum and maximum values of the concerned parameter; and (3) it will validate the resulting stresses using published stress-strain data of bone and determine the bone fracturing status.
Influence of Individual Parameters on Stress Characteristics Within Cancellous and Cortical Bone

Good agreement was found with previous research\textsuperscript{2,3,20–24} in that an increase in D and L led to a reduction in von Mises stresses within the cancellous bone. However, when D increased, the stresses along the line VV oscillated more significantly, following the thread profile. Himmlova et al\textsuperscript{1} and Tawil et al\textsuperscript{23} indicated that D is more important for improved stress distribution than L. However, the present study demonstrates that an increase in L reduced the stresses, within both cancellous and cortical bone, for a wider range of parameters. This was more obvious than the influence of varying D. The finding is also in contrast with that of Pierrisnard et al,\textsuperscript{3} who concluded that the stress within the bone was virtually constant, independent of L and bicortical anchorage.

The present study also showed that when Tcor decreased, the cortical bone supported less load, which in turn caused a slight increase in stresses in the cancellous bone. Generally, as the strength of either cancellous or cortical bone increased, their ability to carry the load also increased. When Ecan increased, the stresses also increased as a result of the cancellous bone being able to support more load. When Ecor decreased, the stresses increased within the cancellous bone as a result of the cancellous bone having to support a greater portion of the load. On the other hand, the stresses within the cortical bone increased as Ecor increased because the cortical bone offered more resistance to the load. It was found that elevated stresses were located at the implant neck for all the parameter combinations. This phenomenon is supported by Meijer et al\textsuperscript{25} who concluded that the regions of bone exposed to maximum stresses are located around the implant neck.

Inter-relationship Between Implant Diameter and Other Parameters

The inter-relationships between the average D of 4.5 mm (as a typical case) and all other parameters are summarized in Figs 4a and 4b for cancellous and cortical bone, respectively. Note that for each parameter other than D, two pairs of curves, which represent the minimum and maximum values of the concerned parameter, while the remaining parameters are assigned average values, are plotted along the lines VV and HH. For example, for Ecan = 1 and 14 GPa, L = 11 mm, Tcor = 1.2 mm, and Ecor = 14 GPa. This is the same for all similar diagrams thereafter (Figs 5 and 6). As expected, an increase in L, Tcor, and Ecor led to a decrease in the von Mises stresses along the line VV (i.e., in cancellous bone) (Fig 4a). When L increased, an
increased portion of the load was supported by the implant and the load within the cancellous bone was distributed across a larger surface area, yielding reduced stress. When Tcor increased, the cortical bone had a larger surface area contact with the implant; hence the cortical bone carried more stresses, leading to a reduced stress level along the line VV. The inter-relationship of Ecan and Ecor with all other parameters will be discussed in the last two subsections.

Increases in L or Tcor led to a decrease in the stresses along line HH (Fig 4b). When L increased, an increased portion of the load was supported by the implant; hence, the stress level in the cortical bone was reduced. When Tcor was increased, the stress level was reduced because the surface area contact between the implant and cortical bone increased. As Ecor increased, its ability to support the load increased and, as a consequence, the stress level in the cortical bone increased. Such inter-relationships between the stresses and Ecor were the same for all similar situations thereafter (Figs 5b and 6b).

A plot of stress contours in the cortical bone is presented in Fig 4c. It is evident that the stress was concentrated at the top left corner of the cortical bone. Note that the stress distributions shown in Fig 4b were measured on line HH, which was located halfway through the cortical thickness. This, together with the inclined nature of the masticatory force, resulted in the maximum stresses occurring at around 0.3 to 0.4 mm from H1, as seen in Fig 4b.

Table 1 shows the von Mises stresses in the cancellous and cortical bone and summarizes the inter-relationships between D and other parameters. Only the stresses at locations V1, V2, H1, and H2, with reference to Fig 2, are presented for all parameters. This is the same for Tables 2 to 5. Table 1 shows that for the majority of parameters, the stress variations caused by changes in D at locations V1, V2, and H2 were less significant than those at H1. The large stress variation at H1 was caused by the different geometry of the implant top when D increased. The results shown in this table further confirm the nondistinctive inter-relationships between the variation of D and all other parameters, as found in a previous study.8

**Inter-relationship Between Implant Length and Other Parameters**

The inter-relationships between the average L of 11 mm (as a typical case) and all other parameters are summarized in Figs 5a and 5b for cancellous and cortical bone, respectively. The characteristics of the von Mises stresses along the lines VV and HH, with variations of Tcor, Ecan, and Ecor were discussed in the preceding section.
When $D$ increased, the stresses along line $VV$ oscillated more significantly, following the thread profile. This increased oscillation was a result of reduced distance between the implant thread and the outer boundary of the cortical bone (Fig 2) and subsequent reduced volume of cancellous bone. This reduced the capacity of cancellous bone to distribute the stresses more evenly. The stresses along the line $HH$ exhibited a reduction when $D$ was increased. This reduction was caused by the larger-diameter implant supporting an increased portion of the load; hence, less stress in the cortical bone.

It should be noted that the 5.5-mm-diameter implant is geometrically different from the smaller-diameter counterparts in the neck region. Because of the existence of a sharp corner on the implant neck, the highest stress occurred at $H_1$, as shown in Figs 5b and 5c, which was different from the stress distributions of smaller-diameter implants.

Table 2 presents the stresses in cancellous and cortical bone and summarizes the relationship between $L$ and other parameters. When $L$ increased, the stresses at $V_1$, $V_2$, $H_1$, and $H_2$ decreased for all values of $D$, $T_{cor}$, $E_{can}$, and $E_{cor}$. This is understandable because an increase in $L$ would lead to a greater surface area contact between the implant and bone.

**Inter-relationship Between $T_{cor}$ and Other Parameters**

The inter-relationships between the average $T_{cor}$ of 1.2 mm (as a typical case) and all other parameters are summarized in Figs 6a and 6b for cancellous and cortical bone, respectively. The characteristic inter-relationships, in terms of the von Mises stresses along the lines $VV$ and $HH$, for $D$, $L$, $E_{can}$, and $E_{cor}$ were identified in previous subsections.

Table 3 shows the stresses in cancellous and cortical bone and summarizes the inter-relationships between $T_{cor}$ and the other parameters. In cancellous bone, when $T_{cor}$ increased, the stresses at $V_1$ and $V_2$ decreased for all parameters, except for the stresses at $V_1$, where a slight increase occurred when $T_{cor}$ = 2.1 mm. In the cortical bone, on the other hand, a less evident trend in stress variations was noticed as $T_{cor}$ increased for all parameters.

**Inter-relationship Between $E_{can}$ and Other Parameters**

An increase in $E_{can}$ increased the stresses along line $VV$ (Figs 4a, 5a, and 6a). This was because the cancellous bone possessed increased resistance to the load. This in turn led to a reduced stress level in the cortical bone (along line $HH$) (Figs 4b, 5b, and 6b). It was also noted that for both cancellous ($VV$) and cortical bone ($HH$), variations of $E_{can}$ had more influence on the stresses than did variations of $E_{cor}$. This is because the cancellous bone had a much larger surface area contact with the implant than the cortical bone. Such a phenomenon can be seen in Figs 4, 5, and 6, respectively, when $D$, $L$, and $T_{cor}$ are constant.

Table 4 shows the von Mises stresses in the cancellous and cortical bone and summarizes the inter-relationships between $E_{can}$ and other parameters. When $E_{can}$ increased, the stresses at $V_1$ and $V_2$ increased for all values of $D$, $L$, $T_{cor}$, and $E_{cor}$, and such an increase was much greater at $V_1$. This is because the cancellous bone supported a greater portion of the load when the stiffness of the cancellous bone was increased. Further, as $E_{can}$ increased, the load supported by the cortical bone decreased at locations $H_1$ and $H_2$, thereby resulting in greatly reduced stresses for all values of $D$, $L$, $T_{cor}$, and $E_{cor}$.

**Inter-relationship Between $E_{cor}$ and Other Parameters**

Increases in $E_{cor}$ decreased the stresses along line $VV$ (Figs 4a, 5a, and 6a). This is because the cortical bone had an increased resistance to the load, thereby...
decreasing the stress level within the cancellous bone. This in turn led to an increased stress level in the cortical bone (along line HH) (Figs 4b, 5b, and 6b).

Table 5 presents the von Mises stresses in the cancellous and cortical bone and summarizes the interrelationships between Ecor and other parameters. When Ecor increased, the stresses at V₁ and V₂ decreased and the stresses at H₁ and H₂ increased significantly for all values of D, L, Tcor, and Ecan. This is because the cancellous bone supported less load and hence the cortical bone supported more when the stiffness of the cortical bone was increased.

### DISCUSSION

#### Ranking of Various Parameters

All five parameters given in Fig 2 were ranked to evaluate the most and the least influential parameters. Based on the data shown in Figs 4 to 6, the average differences (AD) between the von Mises stresses when a single parameter is set to its minimum and maximum values while all other parameters are set to their mean values, are discussed herein. The differences in stress at distances 1, 4.5, and 9 mm from V₁ and 0.2, 0.6, and 1 mm from H₁ along the lines VV and HH, respectively, are given in Table 6. Because of the linear behavior of the implant-bone system, once the stresses caused by maximum loading (F_H = 250 N, F_V = 500 N, and M = 1625 Nmm) are determined, those resulting from the minimum loading (F_H = 25 N, F_V = 50 N, and M = 162.5 Nmm) can be readily obtained.

The stress differences resulting from the minimum and maximum F–M are also included in Table 6. When considering the AD in stresses along line VV, the ranking order was F–M > L > Ecan > Tcor > D > Ecor, where “>” indicates a greater difference in stresses than the subsequent parameter. The applied loading (F–M) had a more significant influence on the stress difference than all other parameters. Young’s modulus of cortical bone (Ecor) exhibited the lowest AD, which was especially evident at a distance of 1 mm along line VV. The ranking order for the AD in stresses along line HH was F–M > Ecan > Ecor > Tcor > D > L. As was found for cancellous bone, variations in F–M had a major influence on the stress difference within the cortical bone. Variations in Tcor, especially at 1 mm along line HH, had the least influence on the stress difference as a result of factors discussed in the inter-relationships between D and other parameters.

#### Stress Validation

Considered for stress validation is the compressive stress on which the bone fracture data is based. In the present study, the compressive stresses were found to be greater in magnitude on the right hand side of the implant than the left, whereas the tensile stresses were greater on the left. For the entire model, the absolute value of the maximum compressive stress was greater than that of the tensile stress on either side of the implant. Hence, the compressive stresses on the right side of the implant were measured along lines VV and HH to compare with the published stress-strain data.
### Table 2  The von Mises Stresses (MPa) in Cancellous and Cortical Bone When Varying Implant Length (L)

<table>
<thead>
<tr>
<th>L (mm)</th>
<th>D (mm)</th>
<th>Tcor (mm)</th>
<th>Ecan (GPa)</th>
<th>Ecor (GPa)</th>
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</table>

Cancellous bone (V2 in brackets)

Diameter = implant diameter; Tcor = cortical bone thickness; Ecan = Young’s modulus of cancellous bone; Ecor = Young’s modulus of cortical bone.

### Table 3  The von Mises Stresses (MPa) in Cancellous and Cortical Bone When Varying Cortical Bone Thickness (Tcor)

<table>
<thead>
<tr>
<th>Tcor (mm)</th>
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<th>L (mm)</th>
<th>Ecan (GPa)</th>
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<td>(4.95)</td>
<td>(9.33)</td>
<td>(4.71)</td>
</tr>
</tbody>
</table>

Cortical bone (H2 in brackets)

Diameter = implant diameter; L = implant length; Ecan = Young’s modulus of cancellous bone; Ecor = Young’s modulus of cortical bone.
Very similar to the experimental results of Currey, the uniaxial compressive stress values for the human femora and tibiae measured by Burstein et al. (Fig 7) were used as a reference in the present study to determine which parameters might lead to either cancellous or cortical bone fracturing. Note in this study that the compressive stresses were obtained under a biaxial stress condition; therefore, a discrepancy is expected when the present results are compared to the uniaxial compressive stresses obtained by Burstein et al. Figure 7 shows the uniaxial compressive stresses of 40 MPa and 190 MPa at fracture for cancellous and cortical bone, respectively.
Table 7 presents the absolute maximum compressive stresses measured along lines VV and HH that were found close to the implant neck. Figures 8a and 8b present the compressive stress distributions within cancellous and cortical bone, respectively. Note that, for each parameter shown in Table 7 and Fig 8, all other parameters were set to their average with the traumatic loading condition ($F_H/F_V/M = 250 N/500 N/1,625 N/mm$).

For the majority of parameters, the fracture stress of cancellous bone (40 MPa) was exceeded (refer to Figs 8a and 8b) at locations close to the implant top along line VV, with Ecan exhibiting the highest stress of all the parameters (refer to Table 5). However, the fracture stress for cortical bone was not exceeded by any parameter.

CONCLUSIONS

This study offers further understanding of the complicated stress distribution characteristics in the mandible under a traumatic loading condition, as influenced by multiple implant and bone parameters. Realistic geometries, material properties, loading conditions, and support conditions for the implant and jawbone are considered in this study. The majority of stress characteristics were found to correlate well with previous research $^{23,8,20-21}$; some findings were new.

In general, it was found that implant length had a noteworthy characteristic inter-relationship with the stresses in the cancellous bone. Compared to implant diameter, increasing the implant length led to a greater surface area contact between the implant and cancellous bone. Hence, implant length is more influential within cancellous bone than the diameter. However, implant diameter is more influential in cortical bone.

Based on an investigation of the inter-relationships between any single parameter and all other parameters, a ranking scheme of all parameters could be established for both cancellous and cortical bone to examine the influence of each parameter. It was found that the applied masticatory force had a more significant influence on the stress difference, in both cancellous and cortical bone, than all other parameters. Young’s modulus of cortical bone and implant length were found to be least influential in cancellous and cortical bone, respectively.

When comparing the absolute maximum compressive stress values within both cancellous and cortical bone with published stress-strain data, the authors found that the cancellous bone fractured for all parameter combinations when traumatic loading was applied. For cortical bone, the fracture point was not reached when subjected to traumatic loading. It should be noted that these statements are true when all parameters were set to their average values. Although not presented herein, the cortical bone

Table 7 Absolute Maximum Compressive Stresses (MPa) in Cancellous and Cortical Bone

<table>
<thead>
<tr>
<th>Line</th>
<th>D (mm)</th>
<th>L (mm)</th>
<th>Tcor (mm)</th>
<th>Ecan (GPa)</th>
<th>Ecor (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV</td>
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<td>13.83</td>
<td>2.1</td>
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<td>10.5</td>
<td>32.40</td>
<td>2.1</td>
<td>20.59</td>
</tr>
</tbody>
</table>

D = implant diameter; L = implant length; Tcor = cortical bone thickness; Ecan = Young’s modulus of cancellous bone; Ecor = Young’s modulus of cortical bone.
fractured when all the parameters were set to the minimum values. It is anticipated that these new findings will assist the clinician to perform a patient-specific implant treatment. Evaluation of the influence of other parameters, which affect the stress characteristics that govern osseointegration and bone growth, can constitute future work. These parameters include implant taper, pitch, and thread design; implant neck offset; different percentages of osseointegration; and implant orientation within the bone. The quantitative evaluation and ranking of the major implant and bone parameters will help provide a practical guideline that will be useful for the design and testing of dental implants. The study may also be of interest to dental professionals in evaluating possible implant placement options under various clinical scenarios.

ACKNOWLEDGMENTS

Special thanks to John Divitini and Fredrik Engman from Neoss Limited for their technical advice.

REFERENCES


