Influence of Implant Design and Bone Quality on Stress/Strain Distribution in Bone Around Implants: A 3-dimensional Finite Element Analysis

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Purpose: *A 3-dimensional finite element analysis was performed to evaluate the influence of implant type and length, as well as that of bone quality, on the stress/strain in bone and implant.* ***Materials and Methods:*** *Two types (screw and cylinder) and 4 lengths (9.2, 10.8, 12.4, and 14.0 mm) of titanium implants were buried in 4 types of bone modeled by varying the elastic modulus for cancellous bone. Axial and buccolingual forces were applied to the occlusal node at the center of the abutment.* ***Results:*** *Regardless of load direction, maximum equivalent stress/strain in bone increased with a decrease in cancellous bone density. Under axial load, especially in the low-density bone models, maximum equivalent strain in cancellous bone was lower with the screw-type implant than with the cylinder-type implant. It was also lower with the longer implants than with the shorter implants. Under buccolingual load, equivalent stress/strain was influenced mainly by bone density.* ***Discussion:*** *This study confirms the importance of bone quality and its presurgical diagnosis for implant long-term prognosis. Implant length and type can also influence bone strain, especially in low-density bone.* ***Conclusions:*** *The results of this study suggest that cancellous bone of higher rather than lower density might ensure a better biomechanical environment for implants. Moreover, longer screw-type implants could be a better choice in a jaw with cancellous bone of low density.* (Int J Oral Maxillofac Implants 2003;18:357–368)

Key words: *biomechanics, bone density, dental implants, finite element analysis, implant design*

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The predictability of implant treatment is supported by many clinical studies reporting survival and success rates higher than 90% for many implant systems.[1–4] However, marginal bone loss around implants that continued for years has also been reported.[1] The occurrence of marginal bone loss is often attributed to poor oral hygiene[5–7] and biomechanical factors.[1,6,8–11] The latter can be related mostly to the implant (eg, shape, length, diameter, material, surface characteristics) and to the patient (eg, bone quality, occlusal force, medical condition).

Albrektsson and coworkers observed greater bone loss around cylindric implants as compared to screw-type implants and assumed that an inadvertent load transmission from the cylindric implants

Parts of this study were presented at the 77th General Session of the International Association for Dental Research, Vancouver, Canada, March 10–13, 1999, and the 102nd Conference of the Japan Prosthodontic Society, Nagoya, October 22–23, 1999.

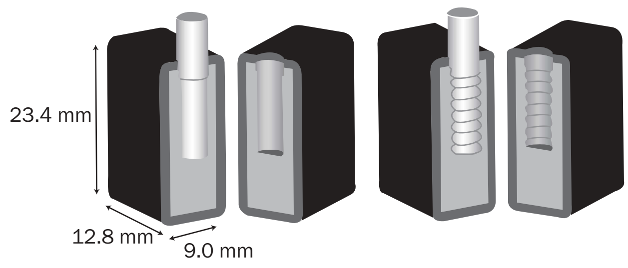


Fig 1 Buccolingual sections of mandibular segments in which *(left)* a cylindric and *(right)* a screw-type implant were buried.

to the surrounding bone could be a possible explanation of this finding.[12] However, this assumption was not experimentally verified.

Another factor related to implant failure is implant length; shorter implants are more prone to failure.[13–16] Since implant length correlates with the area of implant-bone interface, shorter implants could be assumed to generate higher stress/strain in the bone.

Bone quality also influences the long-term success of implant treatment, with poor bone quality leading to lower success rates. The classification for bone quality (types I to IV bone) proposed by Lekholm and Zarb[17] has been widely applied by clinicians in evaluating patient bone for implant placement. Jaffin and Berman found that only 3% of Brånemark System implants (Nobel Biocare, Göteborg, Sweden) placed in type I, II, and III bone were lost after 5 years, while in type IV bone, failure rates were 35% over the same period.[18] van Steenberghe and associates[9] also found more failures in maxillae with poor bone quality. Since the bone around implants must react to stresses and strains generated by occlusal loads, bone with poor quality could more easily fail to withstand these loads.

To verify the hypothesis that bone stress and strain are influenced by implant type (screw or cylinder) and length, as well as bone quality, a 3-dimensional finite element analysis (3-D FEA) was performed. Since failures have also been observed in implants themselves, mainly related to high stress concentration that can lead to fractures, stresses in implants were also investigated by the same method.

MATERIALS AND METHODS

Implants and abutments were modeled on a personal computer (G6-200, Gateway, Sioux City, ND) using a finite element program (ANSYS version 5.5, ANSYS, Canonsburg, PA). In an attempt to simulate a simplified mandibular segment, a cancellous core surrounded by a 1.3-mm-thick cortical layer was modeled around the implants (Fig 1). The overall dimensions of this block were 23.4 mm in height, 25.6 mm in mesiodistal length, and 9.0 mm in buccolingual width. Two types of titanium implants (screw and cylinder) were buried in this bone model (Fig 1).

For the dimensions of the implants, the solid screw of the ITI system (Institut Straumann, Waldenburg, Switzerland) was used as a model, but modifications were made as follows. Each implant type was modeled in 4 lengths (9.2, 10.8, 12.4, and 14.0 mm) with a 6-mm-high abutment. The screw-type implant was an approximation of a helicoid with symmetrically modeled threads. Its depth and pitch are shown in Fig 2. At the cortical bone level, no threads were modeled and the diameter was 4.0 mm. At the cancellous bone level, its outer and inner diameters were 4.0 mm and 3.2 mm, respectively. The cylindric implant was modeled with diameters of 4.0 mm in the cortical region and 3.6 mm in the cancellous region. These diameters and lengths were chosen so as to obtain an implant of equal volume with the screw-type implant of the same length.

Material Properties

All materials used in the models were considered to be isotropic, homogeneous, and linearly elastic. Elastic moduli of 102 GPa and 13.0 GPa were used for the titanium implant[19–21] and the cortical bone,[22] respectively. Four types of bone (1 to 4) were modeled by varying the elastic modulus for cancellous bone (9.5, 5.5, 1.6, and 0.69 GPa). These values were chosen from the results found by Rho and colleagues, who measured elastic modulus (by

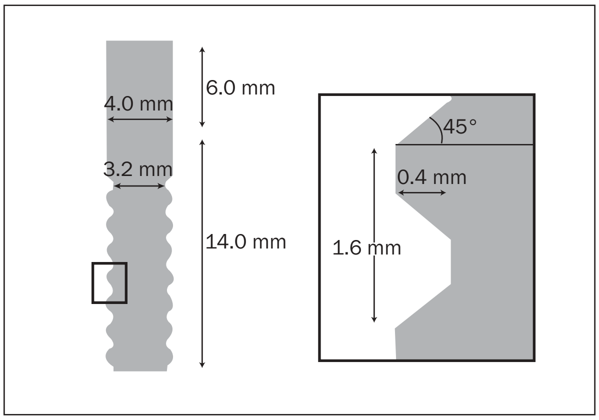


Fig 2 Overall design of the screw-type implant of 14.0-mm length with *(left)* built-in abutment and *(right)* close-up view of the implant thread. Its depth and pitch were 0.4 mm and 1.6 mm, respectively.

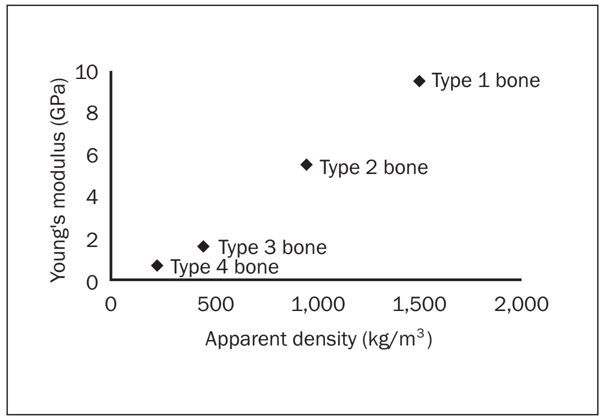


Fig 3 The correlation between elastic moduli and apparent densities of bone, as found by Rho and associates,[23] was used to select the elastic moduli of cancellous bone for the 4 types of bone (types 1 to 4) that were modeled in this study.

ultrasonic technique) of bone with different apparent densities.[23] The correlations between elastic moduli and apparent densities are shown in Fig 3.

Elements and Nodes

Because of its mesiodistal symmetry, only half of the model was meshed with hexahedron elements to shorten the time needed for modeling and analysis. Differences in the mesh pattern may result in quantitative differences in the stress/strain values in the models, which could compromise the comparison between them. Thus, in the present study, all the models were derived from a single mesh pattern that was generated with 12,212 elements and 14,281 nodes. To achieve this, in the phase of model design, implant and bone were shaped using many independent volumes, similar to a mosaic. In the vicinity of the bone-implant interface, the form and size of these volumes allowed them to act as part of the implant or bone, depending on the material properties ascribed to them. According to the desired implant type and length, these volumes were made to be part of either the implant body or the bone. Furthermore, the accuracy of the results of FEA also depends on the fineness of the mesh.[24] Therefore, small elements of similar size were used to uniformly mesh the area of interest for the stress analysis (Fig 4).

Constraints and Loads

The models were constrained in all directions at the nodes on the distal-end surface of the bone segment. Since only half of the model was meshed, symmetry boundary conditions were prescribed at the nodes on the symmetry plane. Because of these symmetry conditions, the constraints at the mesial end were identical with those at the distal end.

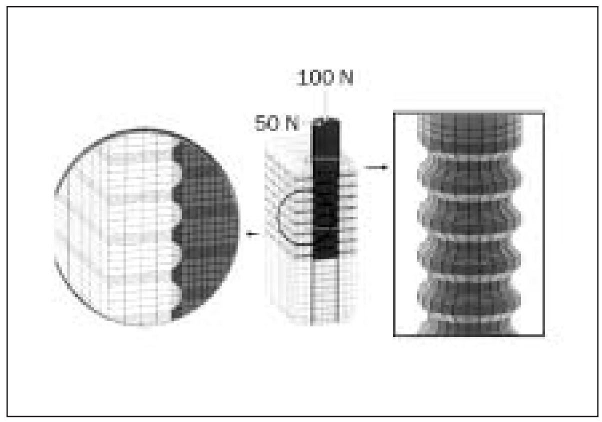
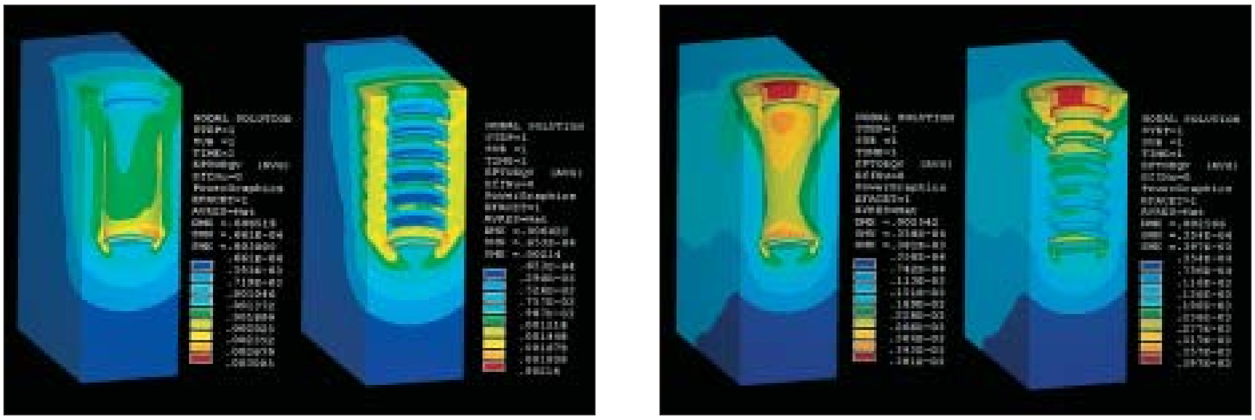


Fig 4 Cross sectional view of the symmetric plane of a model with the screw-type implant. Close-up views of *(left)* the implant-bone interface and *(right)* the implant surface are also shown.

Forces of 100 N and 50 N were applied axially (AX) and buccolingually (BL), respectively, to the occlusal node at the center of the abutment (Fig 4). The same FEA program was used to calculate the von Mises stress (equivalent [EQV] stress) and principal stress in cortical bone and implants and the von Mises strain (EQV strain) and principal strain in cancellous bone. The stresses/strains were averaged at the nodes (nodal solution) for elements of the same material. EQV stress/strain distributions in the models were illustrated with the contour maps.



Figs 5a and 5b Equivalent strain distribution in the cancellous region under axial load. Results are shown with the 12.4-mm-long cylindric and screw-type implants in type 3 bone (Fig 5a) and type 1 bone (Fig 5b) models. The cortical bone is not shown. Note the scale differences between the cylindric (strains from 0.66×10^{-4} to 0.30×10^{-2} in Fig 5a and 0.36×10^{-4} to 0.38×10^{-3} in Fig 5b) and screw-type implants (strains from 0.65×10^{-4} to 0.21×10^{-2} in Fig 5a and 0.35×10^{-4} to 0.40×10^{-3} in Fig 5b).

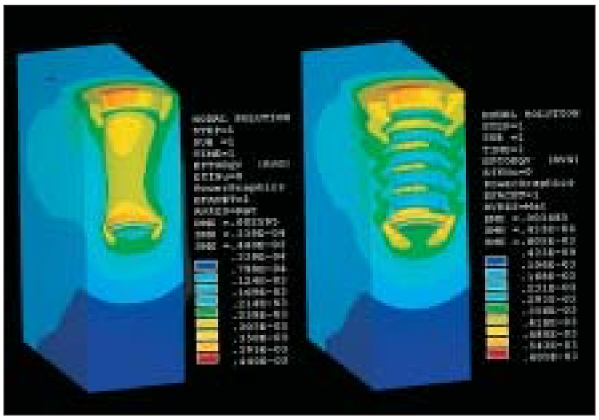


Fig 6 Equivalent strain distribution in the cancellous region under axial load. Results are shown for *(left)* the cylinder-type implant in the type 1 bone model and *(right)* the screw-type implant in the type 2 bone model (both implant lengths are 10.8 mm). The cortical bone is not shown. Note the scale differences between cylindric (strains from 0.34×10^{-4} to 0.44×10^{-3}) and screw-type implants (strains from 0.43×10^{-4} to 0.61×10^{-3}).

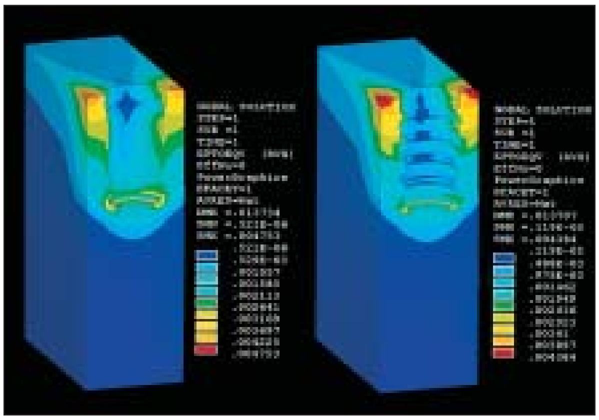


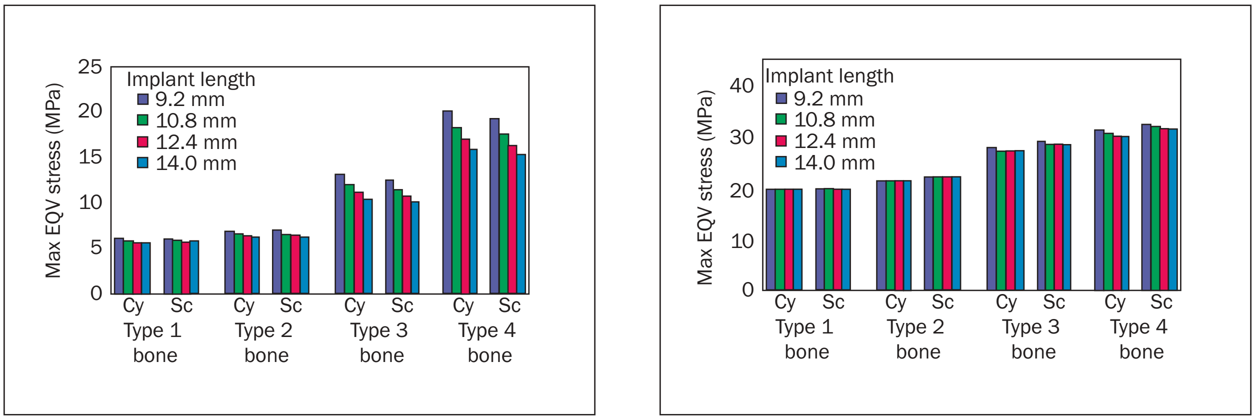
Fig 7 Equivalent strain distribution in the cancellous region under buccolingual load. Results are shown with 9.2-mm-long cylindric and screw-type implants in the type 4 bone model. The cortical bone is not shown. Note the scale differences between cylindric (strains from 0.52×10^{-6} to 0.48×10^{-2}) and screw-type implants (strains from 0.12×10^{-5} to 0.44×10^{-2}).

RESULTS

Stress/Strain Distribution in Bone

Cortical Bone. Under AX load, the highest cortical bone stress was located buccally and lingually around the implant neck in types 3 and 4 bone. In types 1 and 2 bone, this stress was observed mesially and distally around the implant neck (data not shown). Under BL load, highest stress was located buccolingually around the implant neck in all models (data not shown).

Cancellous Bone. EQV strain distribution in the cancellous region under AX load showed some differences, depending on bone quality and implant type. Typical strain distributions for the low- and high-density bone models with the 12.4-mm-long cylindric and screw-type implants are shown in Fig 5a for type 3 bone and Fig 5b for type 1 bone, respectively. For the low-density bone models and for type 2 bone with the cylindric implant, the highest strain was observed around the implant base (Fig 5a). In type 2 bone with the screw-type implant and in type 1 bone with both implant types, the highest strain was often found near the implant neck (Fig 5b), but in some instances, it reached the implant base. However, in the latter, fairly high strains were also present in the neck region (Fig 6). Moreover, in types 3 and 4 bone, the threads of the screw-type implants effectively reduced the degree of concentration, generating moderate strain in bone around the thread crests and evenly distributed low strain in the other regions (Fig 5a). Fairly



Figs 8a and 8b Maximum equivalent (EQV) stress in cortical bone in all the models under *(left)* axial and *(right)* buccolingual loads. Cy = cylinder-type implant; Sc = screw-type implant.

Table 1 Principal Stresses (in MPa) in Cortical Bone Around the Shortest (9.2 mm) and Longest (14.0 mm) Implants Under Axial and Buccolingual Loads

Bone type/ implant type	Axial load				Buccolingual load			
	Highest tensile stress		Highest compressive stress		Highest tensile stress		Highest compressive stress	
	9.2 mm	14.0 mm	9.2 mm	14.0 mm	9.2 mm	14.0 mm	9.2 mm	14.0 mm
Type 1								
Cylinder	1.00	0.95	–8.66	–8.16	28.1	28.1	–28.1	–28.1
Screw	0.99	0.95	–8.68	–8.24	28.8	28.8	–28.8	–28.8
Type 2								
Cylinder	2.47	1.81	–9.94	–9.07	30.4	30.4	–30.4	–30.4
Screw	1.91	1.81	–9.90	–9.12	31.3	31.3	–31.3	–31.3
Type 3								
Cylinder	9.31	7.36	–16.60	–13.40	38.2	37.4	–38.2	–37.4
Screw	8.84	7.06	–16.00	–13.10	39.5	39.0	–39.5	–39.0
Type 4								
Cylinder	16.50	13.20	–24.60	–19.90	42.6	40.8	–42.6	–40.8
Screw	15.70	12.50	–23.60	–19.20	43.7	42.6	–43.7	–42.6

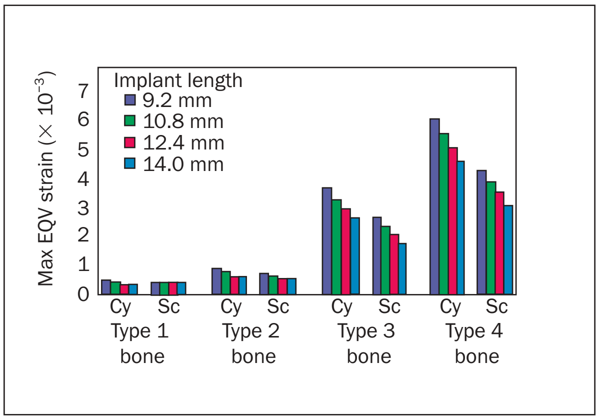
high strain was found over wider areas with the cylinder than with the screw-type implant (Figs 5a and 5b) and in the shorter versus the longer cylindric implants (Figs 5b and 6).

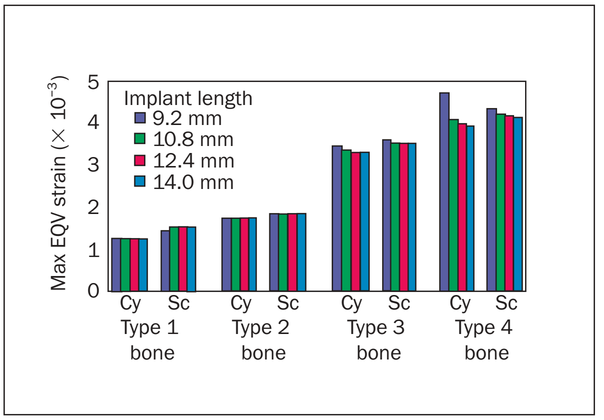
Under BL load, EQV strain distribution in cancellous bone was similar for models with the same bone quality, regardless of implant type and length. In most cases, the highest strain was found around the implant neck, and fairly high strain was distributed in the upper half of the bone. This strain was distributed over larger areas in the low-density bone models, and it reached the implant base in the type 4 bone model with the 9.2-mm-long cylindric implant (Fig 7).

Comparison of Maximum EQV Stress/Strain in Bone

Cortical Bone. Maximum EQV stress in cortical bone is plotted in Figs 8a and 8b for AX and BL loads, respectively. Regardless of load direction, maximum EQV stress increased with the decrease in cancellous bone density, which was more obvious under AX load. However, it was influenced only slightly by implant type. Maximum EQV stress obviously increased as implant length decreased in bone types 3 and 4 under AX load, while it was almost unchanged by the length under BL load.

The highest tensile and compressive stresses in the cortical bone around the implant are listed in Table 1. Only the values for the shortest and longest implants are shown. The values for the other lengths were in between these extremes.





Figs 9a and 9b Maximum equivalent (EQV) strain in cancellous bone in all the models under *(left)* axial and *(right)* buccolingual loads. Cy = cylinder-type implant; Sc = screw-type implant.

Table 2 Principal Strains (× 10^{-3}) in Cancellous Bone Around the Shortest (9.2 mm) and Longest (14.0 mm) Implants Under Axial and Buccolingual Loads

Bone type/ implant type	Axial load: Highest tensile stress 9.2 mm	Axial load: Highest tensile stress 14.0 mm	Axial load: Highest compressive stress 9.2 mm	Axial load: Highest compressive stress 14.0 mm	Buccolingual load: Highest tensile stress 9.2 mm	Buccolingual load: Highest tensile stress 14.0 mm	Buccolingual load: Highest compressive stress 9.2 mm	Buccolingual load: Highest compressive stress 14.0 mm
Type 1								
Cylinder	0.60	0.19	–0.41	–0.29	0.94	0.94	–0.94	–0.94
Screw	0.19	0.15	–0.36	–0.32	1.10	1.10	–1.10	–1.10
Type 2								
Cylinder	0.58	0.37	–0.74	–0.40	1.27	1.27	–1.27	–1.27
Screw	0.40	0.22	–0.63	–0.39	1.30	1.30	–1.30	–1.30
Type 3								
Cylinder	2.40	1.70	–2.80	–1.70	2.60	2.50	–2.60	–2.50
Screw	1.90	1.10	–2.40	–1.20	2.70	2.60	–2.70	–2.60
Type 4								
Cylinder	4.00	2.90	–4.50	–2.90	4.10	2.90	–4.10	–2.90
Screw	3.10	2.00	–3.80	–2.20	3.20	3.10	–3.20	–3.10

Cancellous Bone. Maximum EQV strain in cancellous bone was plotted in Figs 9a and 9b for AX and BL loads, respectively. Regardless of implant type, length, and load direction, maximum EQV strain increased with a decrease in cancellous bone density. Under AX load, in types 3 and 4 bone models, maximum EQV strain was higher with the cylinder-type implant than with the screw-type implant, and it increased with a decrease in implant length.

Under BL load, except for the type 4 bone model with the 9.2-mm-long implant, maximum EQV strain was not influenced much by implant type and length. In the type 4 bone model with the 9.2-mm-long cylindric implant, maximum EQV strain was about 120% of that with other lengths in the same bone model.

The highest tensile and compressive strains in the cancellous bone around the implant are listed in Table 2. As with the cortical bone, only the values for the shortest and longest implants are shown.

Implant Stress. Under AX load, stress in the implant was concentrated only at the loading point, and no significant stress could be found in other regions of the implant. Under BL load, except for the loading point, significantly high stress was found just above the bone surface in both implant types and at the root of the first thread in the screw-type implant (Fig 10). EQV stress at the root of the first thread was about 135% of that at the similar level in the cylindric implant.

A comparison of EQV stress at the root of the first thread for different bone types and implant

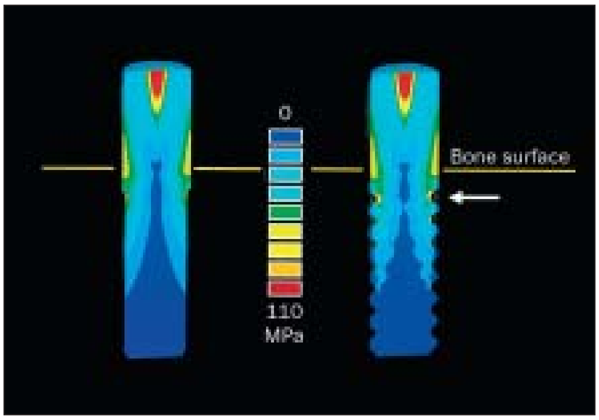


Fig 10 Equivalent stress distribution in the 14-mm-long cylindric and screw-type implants for the type 3 bone model under buccolingual load. Fairly high stress was found just above the bone surface and at the root of the first thread *(arrow)*. (The same scale was used in this figure).

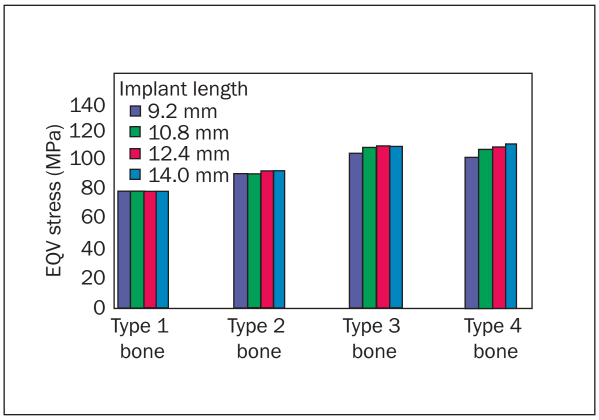


Fig 11 Equivalent stress (EQV) at the root of the first thread in the screw-type implants under buccolingual load.

lengths is shown in Fig 11. EQV stress increased with a decrease in bone density. In bone types 1 and 2, EQV stress at the root of the first thread was similar to that at the implant neck. In bone types 3 and 4, it was higher than that at the implant neck.

DISCUSSION

Clinical studies have reported significant bone loss around the implant neck of failing implants, and various hypotheses have been proposed to explain this bone reaction. Animal experiments[11,21] and clinical studies[1,6,8–10] have shown that bone loss around implants that may lead to implant failure was associated in many cases with unfavorable loading conditions. Inappropriate loading causes excessive stress in the bone around the implant and may result in bone resorption. Therefore, it is valuable to investigate the stresses/strains in bone and their relation to different parameters of implant and bone. The present study used the finite element method (FEM) to investigate the influence of implant type and length, as well as bone quality, on stress in bone and implant.

FEM, originally used in solving engineering problems, is currently often applied in implant biomechanics analyses, contributing to improvements in implant design and prosthetic planning. While computer modeling offers many advantages over other methods in simulating the complexity that characterizes clinical situations, FEM is also sensitive to the assumptions made regarding model parameters, such as material properties and loading and boundary conditions. For instance, in this study, the constraints at the ends of the bone segment and force application on top of the abutment approximated only roughly the complex balance between masticatory forces and their reactions. These simplifications result from limitations of the modeling procedure and thus give only a general insight into tendencies of stress/strain variations under average conditions, without attempting to simulate individual clinical situations. Although it would be tempting to compare the results of the present study with the ultimate stress/strain values for human bone,[25] because of the simplifications intrinsic to FEA it is advisable to focus on qualitative comparison rather than quantitative data from these analyses.[26]

Model Design

In a comparative analysis, complex reality can be simplified, assuming that proportions and relative effect accurately reflect reality.[27] Since simulation of the whole mandibular body is very elaborate, smaller models have been proposed for parameter studies.[27] In the present analysis, a segment of bone was modeled in an attempt to approximate the posterior region of the mandible. Since there is no guideline for an appropriated mesiodistal length of a mandibular segment used in FEA, a trial run comparing 2 lengths (25.6 mm and 12.8 mm) was performed for the models. The results were qualitatively similar, but the bone stress/strain values with the longer segment were about 25% to 30% higher, depending on bone quality and load direction. The longer the mesiodistal length, the more the model segment deformed; this led to heightened stress in the whole mechanical environment. The implant changed this environment in its close vicinity and yielded locally stress/strain concentration. Thus, an overall increase in bone stress/strain was found with the longer segment. However, since no difference in stress/strain tendencies was found between the 2 bone lengths, both models of the trial run were considered to be suitable for this comparative analysis, and the results with the longer segment were reported in the present study. Conversely, the quantitative differences in the results caused by dimension changes of the model also suggest that qualitative comparison of the results of FEA would be more suitable than an examination of the absolute stress values.

The shape of the cancellous bone was simplified to a rectangular block to facilitate the modeling of the same amount of bone for the 2 types of implants, while only the outer edges of the cortical bone were rounded (Fig 1). This was considered to be a reasonable approximation, since the bone stress distribution in this study was similar to that in a previous model,[28] in which the edges of both cortical and cancellous bone were rounded to closer simulate clinical situations.

In studies of the entire mandible, in which convergence tests with mesh refinements have been performed, models with over 13,720[19] or 10,420[24] nodes showed convergent results. Thus, it is obvious that a fine mesh is a major factor in the achievement of an accurate model. The main advantage of small, simplified models is that they allow for finer meshing with hexahedron elements. Thus, in the present study, only a mandibular segment with an extremely fine mesh around the implant (areas of high stress) was modeled (Fig 4). This resulted in a model consisting of 14,281 nodes, a number that was considered to ensure a sufficiently fine mesh for the given geometry, and no further mesh refinement was performed.

In the present study, no debonding was allowed at the implant-bone interface. Other FEAs showed remarkable differences in the values and sometimes even in the distributions of stresses between "fixed bond" and "slip" (contact) interface boundary conditions.[29,30] Unfortunately, the experimental evidence to decide what is the most realistic interface boundary condition remains scant.[29] However, removal torque tests have showed higher scores for implants with rough (titanium dioxide–blasted or titanium plasma-sprayed) than machined surfaces, and the removal of the former implants in that study frequently resulted in fractures within the bone distant from the implant surface,[31] thus suggesting the existence of an implant-bone "bond." Since the present study simulated an implant with a rough surface, a "fixed bond" condition was set at its interface with bone, as a first approximation.

Although implant loss has rarely been found with implants longer than 13 mm, shorter implants seem to be more often related to implant failure.[32] In the aforementioned, it was not specified whether the failures affected bone around the implant or the implant itself. Thus, the present FEA investigated both bone and implant stresses and compared the results of the 14.0-mm-long implant models with those of the 12.4-, 10.8-, and 9.2-mm-long implant models.

Since in clinical practice, the most frequently used implants are the screw and cylinder types,[4] the stress/strain in bone around these implants were compared in the present study. Matsushita and colleagues[33] compared cylindric and screw-type implants in an FEA study by adding an outer thread to the cylindric implant surface. In the comparison of a screw-type implant of a greater diameter and a cylindric implant of a smaller diameter, it was difficult to conclude whether the differences in stress found were the result of the differences in shape or diameter. In the present study, therefore, cylindric and screw-type implant diameters in the cortical bone were the same, and the diameter of the cylindric implant in the cancellous bone was set as the average value between the inner and outer diameters of the screw-type implant. This modeling was an attempt to keep the variables of the analysis to a minimum, and ensured that the influence of implant type on the results could be more clearly investigated.

Clinical studies have shown that implants placed in types I and II bone (bone quality classification by Lekholm and Zarb[17]) have good long-term prognosis, but for implants in unfavorable bone, especially in type IV bone, which has a more porous, cancellous structure, failure rates increase significantly.[9,18,34,35] Cancellous bone density seems to have a strong influence on implant failure, and the elastic modulus strongly depends on the apparent density or porosity of the tissue.[25] Thus, Young's modulus of cancellous bone was changed to evaluate its influence on the stress/strain in bone and implant. Young's moduli of cancellous bone were selected from the study by Rho and associates[23] as follows: the values for bone type 1 (9.5 GPa) and bone type 4 (0.69 GPa) are the lowest cortical bone and the lowest cancellous bone measurements, respectively. Thus, these models approximated types I and IV bone qualities from the Lekholm and Zarb classification. The elastic modulus for the cancellous core in type 1 bone was lower than that of the cortical layer, to compensate for the bone marrow, which though narrow, is still present in type I bone. Type 3 bone (1.6 GPa) corresponds to a bone that is twice as dense as type 4 bone, and type 2 bone (5.5 GPa) corresponds to a bone that is twice as dense as type 3 bone (Fig 3). However, since in the bone quality classification by Lekholm and Zarb, quantitative estimates for bone density or elasticity are not available, it is difficult to find precise correspondence to the bone models of the present study. Furthermore, bone quality also depends on other factors, such as trabecular architecture and amount of cortical bone, which were not accounted for in this study. Thus, the present analysis investigated the relationship between one aspect of bone quality (the elastic modulus of bone and, indirectly, its apparent density) and the stresses/strains in bone and implants.

Stress/Strain Distribution

The present study expressed the results in both equivalent and principal stresses/strains, but the former was preferred for the comparison between models. The equivalent stress/strain is a scalar quantity that includes all components of the stress/strain tensor[36] and allows comprehensive comparison between models. In addition, both compressive and tensile stresses, if in excess, can lead to bone resorption or necrosis.[37,38] Thus, the factors that may lower the overall amount of potentially harmful stress to bone were investigated by comparing the equivalent stress in the models.

Cortical Bone Stress. Since the cortical bone had a much higher elastic modulus than the cancellous bone, it was the load-carrying member for all cancellous bone qualities, regardless of load direction. Highest stress concentration around the implant neck was also found in many 3-D FEAs[19–21,27,28,39,40] and thus this was not emphasized in the present study. Implant type and length did not greatly influence stress distribution in cortical bone, probably because the implant neck had the same shape and diameter in all models and transferred the stress similarly to the surrounding bone.

Cancellous Bone Strain. Since the same Young's modulus was set for cortical bone in all models, EQV stress was appropriate to express the results in this region. However, Young's modulus for cancellous bone differed between models. Thus, if the same load is applied, even though stress will be the same, strain will vary with the Young's modulus. Therefore, EQV strain was chosen instead of EQV stress to show the results of the FEA in cancellous bone.

The "strength of materials" principle states that, if the implant supporting tissue has homogeneous elastic properties, the axial load transmitted from implant to bone concentrates highly in the upper region of bone and decreases rapidly toward the implant base. Thus, the stiffer cancellous region in types 1 and 2 bone, except for the cylindric implants in type 2 bone, was able to support the implant in its upper half, leading to highest or high strain in the region just below the cortical bone (Figs 5b and 6). The higher displacement of the cylindric implants in type 2 bone, which had a smaller contact surface with the surrounding bone, resulted in a behavior resembling that in types 3 and 4 bone. In these models, the softer cancellous region withstood the axial load less efficiently and was remarkably displaced downward. Thus, high or moderate strains, depending on implant type, were found over large areas at the bone-implant interface, and highest strains were located around the implant base (Fig 5a). In these instances, the presence of threads had a favorable influence on force transmission to bone, dissipating force.

Under BL load, in most of the instances, strain was concentrated in the cancellous bone around the implant neck, near the fulcrum of implant bending (Fig 7). For this reason, differences in implant length and shape in the lower part of the implant did not influence the strain distribution.

Correlation Between Implant Type and Maximum EQV Stress/Strain

In models with implants of the same volume, under AX load, lower maximum EQV strain in cancellous bone was found in types 3 and 4 bone with the screw implant than with the cylindric implant (Fig 9a). This finding could be explained by the change of the force-transmitting mechanism from shearing force with the cylinder to interlocking of crest and groove with the screw and by a larger contact area at the implant-bone interface with the screw implant. The threads decomposed the axial load into 2 components: parallel and perpendicular to the plane of the threads. Distribution of the same force over a larger surface led to lower stress. Therefore, the screw-type implant may reduce the risk of overloading cancellous bone.

These results concur with the study of Spiekermann and coworkers, who found less marginal bone loss with titanium plasma-sprayed screw implants than with cylindric IMZ implants.[41] In another study, Røynesdal and associates found that threaded titanium implants had significantly better scores for bone resorption than titanium plasma-sprayed cylindric implants.[42] Since the patients in that study were mostly women with a mean age of 71 years, it could be assumed that their bone condition may have been similar to that simulated in types 3 and 4 bone of the present study.

Although in the types 3 and 4 bone models, maximum EQV stresses/strains under AX load were higher with the cylindric implant (Figs 8a and 9a), under BL load they were slightly higher (up to 5%) with the screw-type implant in almost all cases (Figs 8b and 9b). These results could be explained by easier bending, which occurred at the first root of the thread, thus leading to slightly higher strain in the cancellous bone corresponding to that region. Accordingly, maximum EQV strain/stress was also raised slightly.

Correlation Between Bone Quality and Maximum EQV Stress/Strain

In all instances, stress/strain values in bone increased with a decrease in cancellous bone density (Figs 8 and 9). Low-density bone has low stiffness, generating a significant implant displacement (sinking and tilting under AX and BL loads, respectively). This greater displacement led to higher deformation of the bone and thus to higher stresses and strains in the cortical and cancellous bone, respectively. This result could perhaps be an explanation of the findings in clinical reports, in which higher failure rates were observed for type IV bone than for types I to III bone.[9,18]

Correlation Between Implant Length and Maximum EQV Stress/Strain

Implant length has also been proposed in some reports as a factor affecting implant success. van Steenberghe and coworkers found failure rates of 10.7% with 7-mm-long implants and approximately 5.9% with 10-mm and 13-mm implants in the maxilla, which often comprised poor-quality bone, while none of the implants that were 15 mm or longer failed.[9] However, length did not affect the success rate in good-quality bone. Similarly, in this study, implant length affected maximum EQV stress/strain in types 3 and 4 bone models under AX load (Figs 8a and 9a). Thus, these results would seem to concur with the reports that proposed implant length and bone quality as factors that influence implant success. The lower strain found with longer implants could be explained by a larger bone-implant contact area, which adds resistance to implant displacement.

Under BL load, maximum EQV strain in the type 4 bone model with the 9.2-mm-long cylinder-type implant was significantly higher than in the other models (Fig 9b). This finding can be corroborated with the change in location of high stress, from a region around the implant neck to a larger region that included the implant base, thus suggesting that greater implant tilting occurred in the low-density bone with the shorter implants, especially with the 9.2-mm-long implant.

Implant Stress

In the low-density bone, implant stress at the root of the first thread under BL load was greater than that just above the bone surface (Fig 10). It increased with a decrease in bone density (Fig 11). Thus, implant fracture could occur more easily at the root of the first thread, especially in poor-quality bone. Although implant fracture has been observed only rarely in clinical studies,[1,14,43,44] screw-type implants have a higher risk of implant fracture than cylinder-type implants when exposed to lateral loads because of their thread design. This risk is amplified by low-density bone, which allows more bending of the implant. Thus, when using screw-type implants, it might be suggested that clinicians try to avoid high lateral forces on the implants by careful patient selection and appropriate prosthesis design.

Implications for FEA Modeling

In this study, screw-type and cylindric implants were modeled and stress/strain distributions in the models were compared. Since only slight differences between stresses/strains with the 2 implant types were found in bone models with high bone density (bone types 1 and 2), it could be concluded that in such FEA models, a cylinder could be a reasonable approximation for a screw-type implant. In models with low bone density (like bone types 3 and 4), if a screw-type implant is simplified to a cylinder, strain in the cancellous bone under AX load would be overestimated.

CONCLUSIONS

The results of this FEA suggest the following:

1. Maximum EQV strain in cancellous bone and maximum EQV stress in cortical bone increased in the models with cancellous bone of low density, confirming the importance of bone quality and its presurgical diagnosis for implant long-term prognosis.
2. Under AX load, maximum EQV strain in cancellous bone was lower with the screw-type implant than with the cylinder-type implant, especially in the low-density bone models. Thus, a screw-type implant could be a better choice in a jaw with cancellous bone of low density.

3. Since under AX load the influence of implant length on bone stress appeared clear for low-density bone, in this type of cancellous bone, longer implants could be a better choice over shorter implants.

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