Biomechanical Optimization of Implant Diameter and Length for Immediate Loading: A Nonlinear Finite Element Analysis

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Purpose: A nonlinear finite element method was applied to examine the effects of implant diameter and length on the maximum von Mises stresses in the jaw, and to evaluate the maximum displacement of the implant-abutment complex in immediate-loading models. ***Materials and Methods:*** The implant diameter (D) ranged from 3.0 to 5.0 mm and implant length (L) ranged from 6.0 to 16.0 mm. ***Results:*** The results showed that the maximum von Mises stress in cortical bone was decreased by 65.8% under a buccolingual load with an increase in D. In cancellous bone, it was decreased by 71.5% under an axial load with an increase in L. The maximum displacement in the implant-abutment complex decreased by 64.8% under a buccolingual load with an increase in D. The implant was found to be more sensitive to L than to D under axial loads, while D played a more important role in enhancing its stability under buccolingual loads. ***Conclusion:*** When D exceeded 4.0 mm and L exceeded 11.0 mm, both minimum stress and displacement were obtained. Therefore, these dimensions were the optimal biomechanical selections for immediate-loading implants in type B/2 bone. *Int J Prosthodont 2009;22:607–615.*

In recent years, implant therapy has developed into a well-established and popular approach due to its short rehabilitation time.[1] In particular, immediate loading has greatly increased patient satisfaction since patients do not need to wear a conventional denture during the healing process.[2] Though most research shows no difference in implant stability and implant failure rates with delayed and immediate loading of implants,[3,4] few studies have focused on immediate loading for single-tooth replacements.[5,6]

In addition, data from previous studies suggest several factors that could affect the results of immediate implant loading. These factors include the surgical technique, primary implant stability, bone quality and quantity, wound healing, the implant macrostructure, implant surface texture, and prosthetic design.[7] The principle gateway of stability in immediate implant loading was found to be the mechanical lock rather than osseointegration, suggesting that the implant macrostructure played an important role in enhancing primary implant stability.

In this research, the authors aimed to design a three-dimensional (3D) finite element analysis for the study of the effects of implant diameter and length in single-tooth replacements, and to determine the optimal implant biomechanical parameters in immediate loading.

Materials and Methods

Model Design

A posterior mandible segment with an implant and superstructure was assembled on a personal computer using a 3D program (Pro/ENGINEER Wildfire, Parametric Technology) (Fig 1). A cross-section of the mandible in the first molar region was used as the basis for a solid model. The cross-sectional image was then extruded to create a 3D mandible segment, which contained a thick layer of cortical bone surrounding dense cancellous bone (type B/2 bone according to the Lekholm and Zarb classification[8]).

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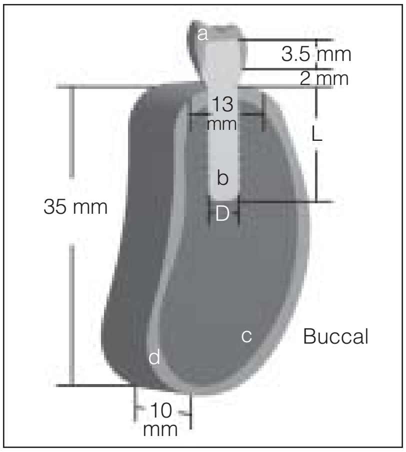

Fig 1 *(left)* The assembled model composed of the superstructure, the implant-abutment complex, cortical bone, and cancellous bone.

Fig 2 *(right)* Cross-sectional view; a = superstructure, b = implant-abutment complex, c = cancellous bone, d = cortical bone, D = implant diameter (range: 3.0 to 5.0 mm). L = implant length (range: 6.0 to 11.0 mm).

Table 1 Mechanical Properties of Materials Used in the 3D Models

Material	Young's modulus (MPa)	Poisson ratio
Cortical bone[9]	13,000	0.30
Cancellous bone[9]	1,370	0.30
Titanium[9]	102,000	0.35
Porcelain[10]	68,900	0.28

The average thickness of the cortical bone in the crestal region was 1.3 mm. The mesial and distal planes were not covered by cortical bone. The dimensions of the bone segment are shown in Fig 2.

The geometry of the ITI solid implant (Straumann) was used as a reference to model a cylindrical-screwed implant and a 3.5-mm-high solid abutment, which were simplified to one unit as shown in Fig 2. A profile of a full-porcelain superstructure (mandibular first molar) was achieved using a 3D sensing system (Shanghai Digital Manufacturing) and the structure light-scanning technique. The solid model was reconstructed using the scanning data by a reverse engineering program (Geomagic Studio 8.0, Raindrop Geomagic). The superstructure model was then applied over the titanium abutment using the Pro/ENGINEER program (Fig 1). Implant diameter (D) and length (L) were set as the input variables. D ranged from 3.0 to 5.0 mm and L ranged from 6.0 to 16.0 mm (Fig 2). All models were meshed and analyzed using ANSYS Workbench10.0 (SAS IP).

All materials used in the models were considered to be isotropic, homogenous, and linearly elastic. The mechanical properties were taken from the literature[9,10] and are listed in Table 1.

The frictional interface between the implant and the bone was modeled using a nonlinear frictional contact element with a coefficient of 0.3.[11] The prosthesis–abutment interface was considered to be bonded.[12]

Models were meshed using 10-node tetrahedron and 20-node hexahedron elements. A finer mesh was generated around the implant (Fig 3). Models were composed of an average of 220,000 elements and 310,000 nodes.

Constraints and Loads

Models were constrained in all directions at the nodes on the mesial and distal bone surfaces. Forces of 100 N and 30 N were applied axially on the fossa and buccolingually at a 45-degree angle on the buccal cusp, respectively (Fig 4).[11] The maximum von Mises stress (Max EQV stress) on the jaw bones and the maximum displacement of the implant-abutment complex were set as output variables to evaluate the effect of different implant designs on the jaw bone and implant. The sensitivity of the output to input variables was also evaluated.

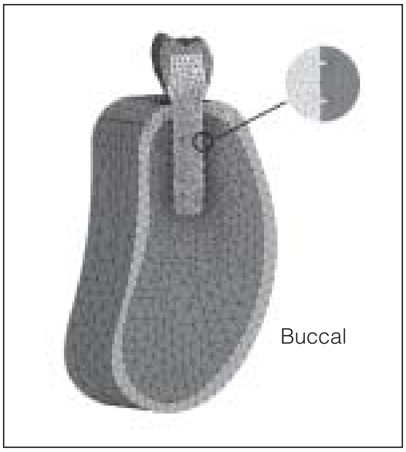

Fig 3 Cross-sectional view of a meshed model.

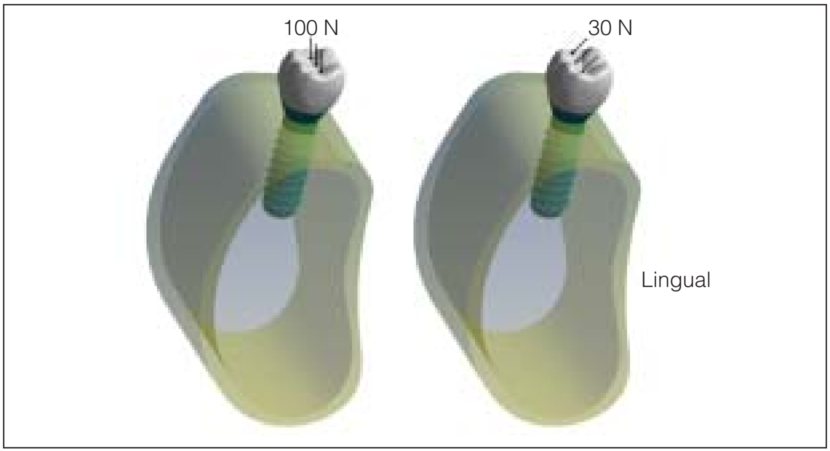

Fig 4 Directions of the loads: **(a)** 100-N axial load; **(b)** 30-N 45-degree buccolingual load.

Table 2 Max EQV Stress in Jaw Bones and Maximum Displacement in the Implant-Abutment Complex of the Samples

			Max EQV stress in cortical bone (MPa)		Max EQV stress in cancellous bone (MPa)		Max displacement in the implant-abutment complex (μm)	
Patient	D (mm)	L (mm)	AX	BL	AX	BL	AX	BL
1	3.0	6.0	14.355	56.236	37.594	18.595	8.138	24.156
2	3.0	11.0	9.315	38.555	20.871	9.564	5.492	18.161
3	3.0	16.0	6.450	32.745	11.764	6.668	4.582	17.911
4	4.0	6.0	12.503	39.173	35.141	15.628	6.241	15.066
5	4.0	11.0	7.025	21.097	14.529	6.859	4.233	9.576
6	4.0	16.0	6.605	21.968	10.611	5.762	3.489	8.956
7	5.0	6.0	7.387	20.654	22.680	13.494	5.033	10.723
8	5.0	11.0	5.212	13.167	12.800	6.119	3.488	6.421
9	5.0	16.0	3.838	10.687	9.670	7.088	2.876	5.681

AX = axial load; BL = buccolingual load.

Convergence Test

A convergence test with mesh refinements was performed on the mandible segment. von Mises stresses in cortical and cancellous bones were used for convergence monitoring and a tolerance of 5% was used. Changes less than 5% indicated convergence. An adaptive convergence was achieved after calculation.

Response Surface Construction and Sensitivity Analysis

Response surfaces were constructed for nine samples via Latin hybercube sampling using ANSYS DesignXplorer.[12,13] Sensitivity charts were also obtained for the impact of input variables on output variables.[12,13]

Results

Nine samples were modeled in this study (Table 2). The input variables (D and L) versus output variables are listed in the response surface charts in Table 3 and Fig 5. When one input variable was equal to the median, response curves of the other input variable versus the Max EQV stress were determined (Table 4, Fig 6). Response curves of the input variable versus the maximum displacement are shown in Table 5 and Fig 7. The full-range sensitivity similarities of the output and input variables can be seen in Fig 8 (D = 4.0 mm, L = 11.0 mm). All figures and charts in this study were generated automatically by the ANSYS DesignXplorer program.

Table 3 % Decrease of the Response Surface of Input Variables to Output Variables*

	% decrease	
	AX	BL
Max EQV stress in cortical bone (MPa)	73.3	81.0
Max EQV stress in cancellous bone (MPa)	74.9	72.2
Max displacement in the implant-abutment complex (mm)	64.6	77.3

AX = axial load; BL = buccolingual load.
*% decrease = (value$_{Max}$ – value$_{Min}$) / value$_{Max}$ × 100.

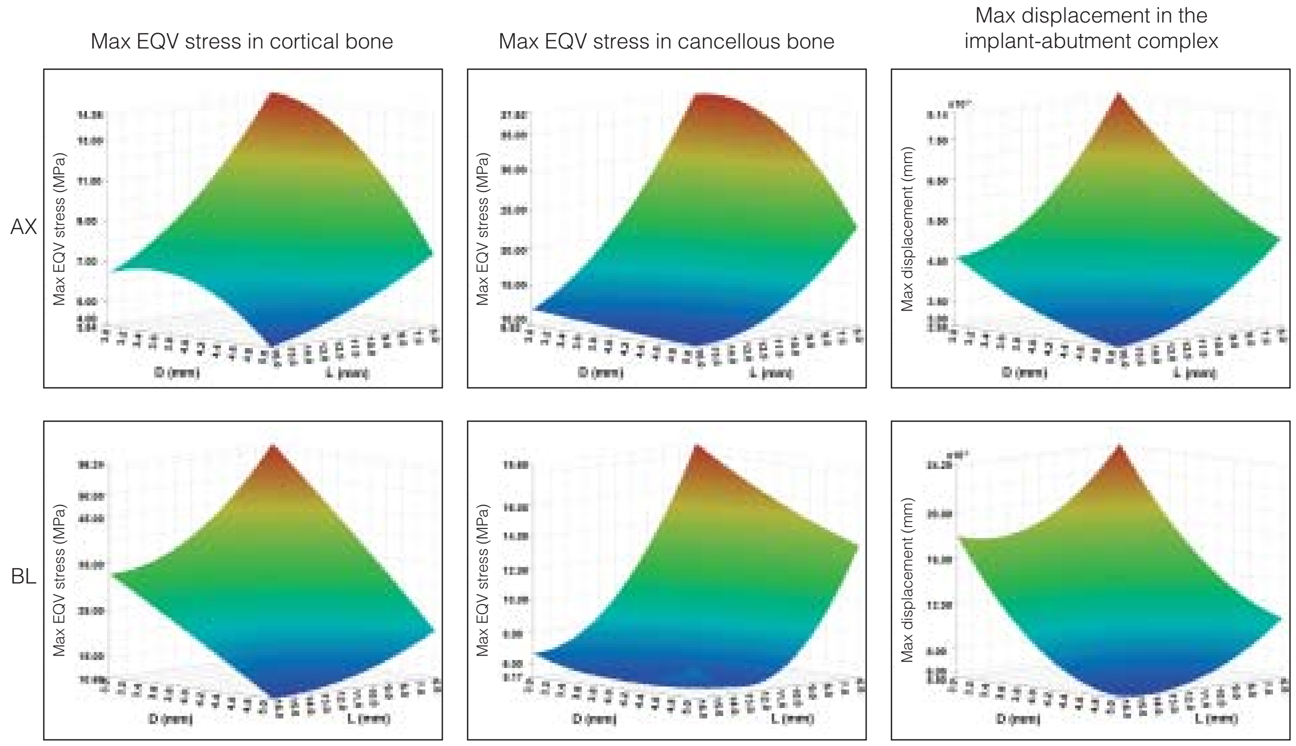

Fig 5 Response surface of input variables to output variables.

Table 4 % Decrease of the Response Curve of Input Variables to Max EQV Stress in Jaw Bones*

	Max EQV stress			
	AX		BL	
Variable	Cortical bone	Cancellous bone	Cortical bone	Cancellous bone
D (3.0–5.0 mm) L = 11.0 mm				
% decrease	44.0	38.8	65.8	36.3
Optimum selection D	≥4.0 mm	≥ 4.0 mm	≥ 4.0 mm	≥3.95 mm
L (6.0–16.0 mm) D = 4.0 mm				
% decrease	50.6	71.5	51.5	66.3
Optimum selection L	≥10.5 mm	≥ 10.8 mm	≥ 10.5 mm	10.8 mm

AX = axial load; BL = buccolingual load.
*% Decrease = (stress$_{Max}$ – stress$_{Min}$) / stress$_{Max}$ × 100.

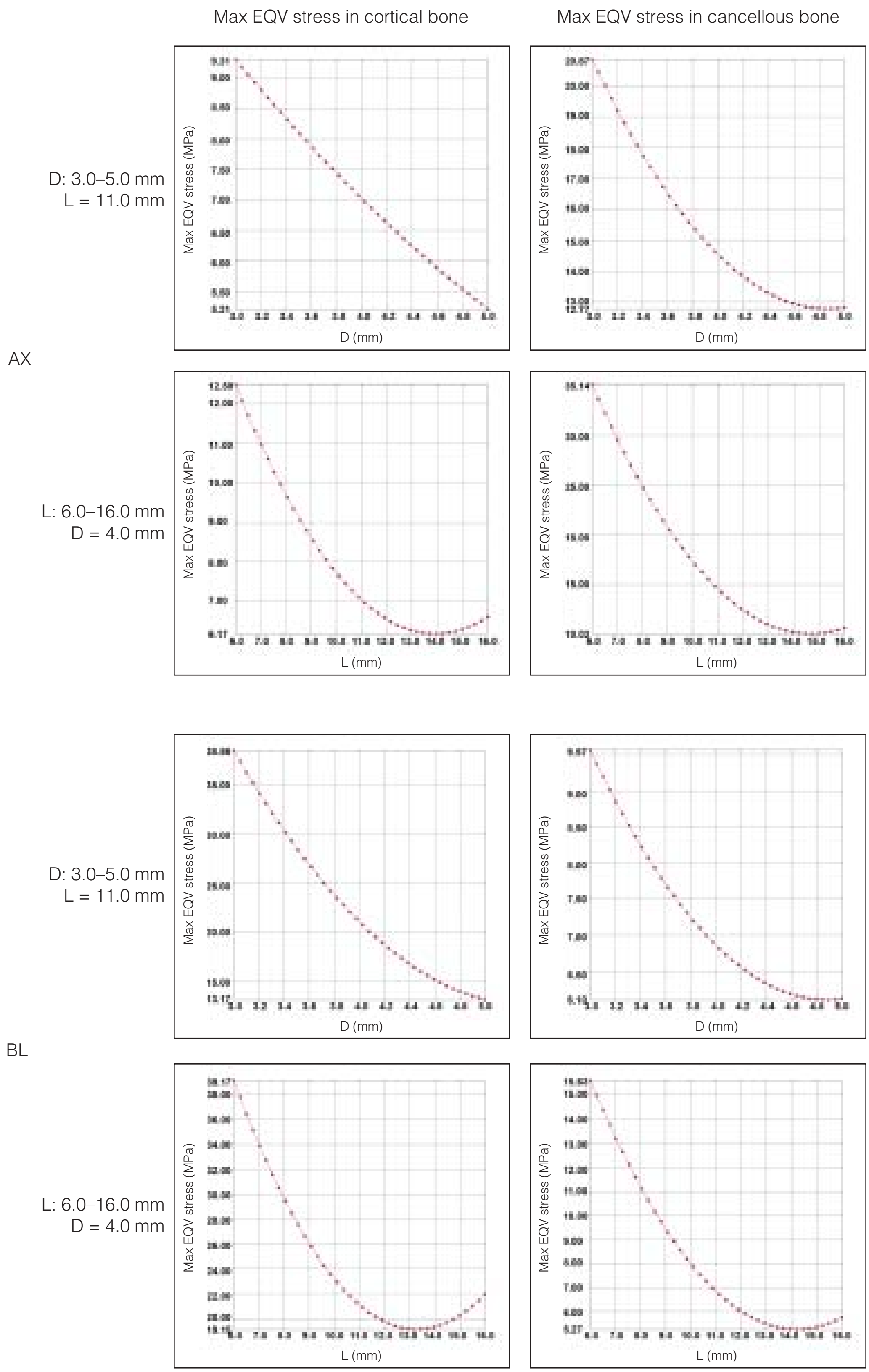

Fig 6 Response curve of input variables to Max EQV stress in jaw bones.

Table 5 % Decrease of the Response Curve of Input Variables to Maximum Displacement in the Implant-Abutment Complex*

	AX	
Variable	Cortical bone	Cancellous bone
D (3.0–5.0 mm) L = 11.0 mm		
% decrease	36.4	64.8
Optimum selection D	≥3.95 mm	≥ 4.0 mm
L (6.0–16.0 mm) D = 4.0 mm		
% decrease	44.1	43.0
Optimum selection L	≥11.0 mm	≥ 10.8 mm

AX = axial load.
*% decrease = (stress$_{Max}$ – stress$_{Min}$) / stress$_{Max}$ × 100.

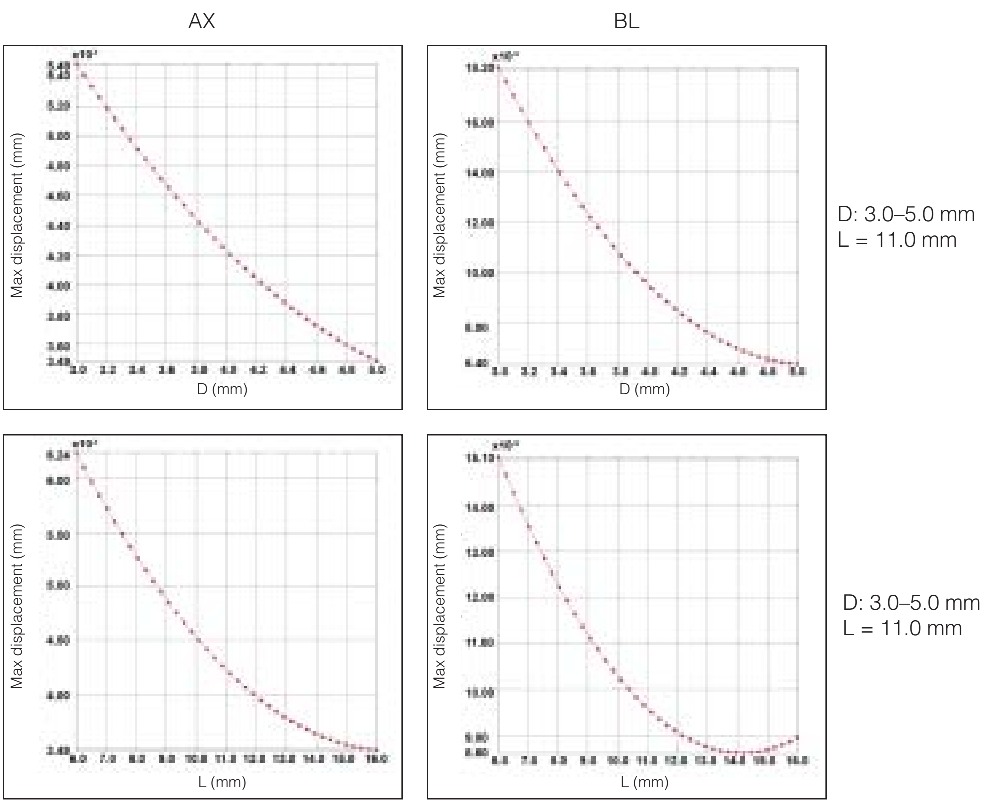

Fig 7 Response curve of input variables to maximum displacement in the implant-abutment complex.

Discussion

Model Design

The finite element method has been used popularly by researchers to predict unknown clinical biomechnical phenomena of dental implants, which greatly shortens research time and provides essential references and verifications.[14] Up until recently, linear static models have been employed extensively in dental implant finite element studies. However, the validity of a linear static analysis is questionable for more realistic situations such as immediate loading.[15] Real situations give rise to nonlinearities. For immediate loading, contact and friction play important roles in the mechanical behaviors of the implant, the jaw, and its prosthetic restoration. However, most previous nonlinear research on dental implants was focused on the joint connection[16,17] of the implant-teeth splinting system[18] and the implant-abutment complex.[19] Little has been published on

Fig 8 Sensitivity analysis of output parameters to variables D and L (D = 4.0 mm, L = 11.0 mm). **(a)** Max EQV stress in the cortical bone under axial load, **(b)** Max EQV stress in the cancellous bone under axial load, **(c)** maximum displacement in the implant-abutment complex under axial load, **(d)** Max EQV stress in the cortical bone under buccolingual load, **(e)** Max EQV stress in the cancellous bone under buccolingual load, **(f)** maximum displacement in the implant-abutment complex under buccolingual load.

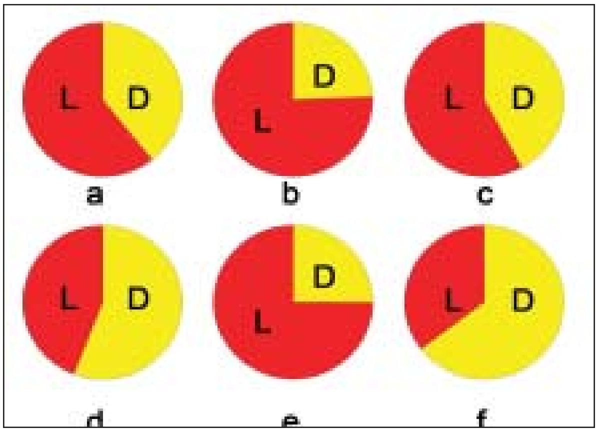

Table 6 Differences Between the Osseointegrated Loading and Immediate Loading Methods

	Kong et al[13]	Current study
Type of FEM model	Osseointegrated loading	Immediate loading
Bone-implant interface conditions	Bonded	Frictional: coefficient = 0.3[11]
More important in reducing cortical bone stress	Diameter	Length for axial load, diameter for buccolingual load
More important in reducing cancellous bone stress	Length	Length
More important in reducing implant displacement	Diameter	Length for axial load, diameter for buccolingual load

FEM = finite element method.

the immediate loading of implants for single-tooth replacements.[5,6] In this study, a frictional contact between the jaw bone and the implant was examined at the interface, and simulation models mimicking realistic screw-implant connections and superstructures were constructed. Therefore, the results of this study are more reliable than those using bonded contact, no separation contact, or a slip contact for immediate loading, and provide valuable information for immediate loading clinical practices.

Implant Design and Immediate Loading

The configuration of an implant has long been considered an essential requirement for implant success. As a general concept, the screw-implant design can develop higher mechanical retentions and greater transferability of compressive forces.[20] The screw design not only minimizes micromotion of the implant, but also improves the initial stability, which is the principal requirement for immediate-loading success. Length of the implant may also affect the outcome of immediate implant loading. One study reported a 50% failure rate with immediate loading when implant lengths were less than 10 mm.[21] Another study also suggested that implants should be ≥ 10 mm in length to ensure high success rates.[22] Several authors even speculated that it could be beneficial to use implants ≥ 14 mm in length and ≥ 4 mm in diameter for immediate loading.[22] Nonetheless, data from these studies were based mainly on clinical experience with limited human research. Therefore, the critical L and D of immediately loaded implants remains to be determined.

Response Surface and Curve Analyses

Results of the bivariate response surface analysis (see Table 3, Fig 5) showed that Max EQV stress in cortical bone decreased by 81.0% under a buccolingual load. The decrease was less in cancellous bone, indicating that the effects of D and L on Max EQV stress in cortical bone under a buccolingual load were more significant than in cancellous bone or cortical bone under an axial load. Under a buccolingual load, the maximum implant displacement decreased by 77.3%, which was much higher than that of the axial load, indicating that implant stability was more easily affected by buccolingual force.

Analysis of the response curves from Tables 4 and 5 and Figs 6 and 7 suggests that Max EQV stress in cortical bone decreased by 44.0% and 65.8% under axial and buccolingual loads, respectively, as the diameter of the implant increased. Both decreased percentages were greater than those found in cancellous bone. These results demonstrate that D affected the Max EQV stress more in cortical bone. With the increase in L, Max EQV stress in cancellous bone decreased by 71.5% and 66.3% under axial and buccolingual loads, respectively, which were higher than in cortical bones. This suggests that L favored stress distribution in cancellous bone. When L increased, Max EQV stress in the cancellous bone decreased by 71.5% and 66.3% under axial and buccolingual loads, respectively. Max EQV stress in cortical bone decreased by 50.6% under an axial load. These decreases were more significant than those from the increase in D, indicating that L favored stress distribution in cortical and cancellous bones under axial loads, as well as in cancellous bone under buccolingual loads, more than D. As expected, these data were highly different from previous research regarding osseointegrated implants (Table 6).[13] With the increase in L, the maximum displacement in the implant-abutment complex under an axial load decreased by 44.1%, much more than that with the increase of D, indicating that L played a more significant role in implant stability than D under axial loads. On the other hand, with the increase of D, the maximum displacement in the implant-abutment complex under a buccolingual load decreased by 64.8%—higher than that with the increase of L—indicating that D is more important in protecting implant stability than L under buccolingual loads.

Furthermore, when D was $>$ 4.0 mm and L was $>$ 11.0 mm, the most stable complex with minimal stress and displacement levels could be achieved. These data support the findings from various clinical studies.[22,23]

Sensitivity Analysis

Sensitivity analysis indicated that L played a more significant role in reducing jaw bone stresses and enhancing implant stability under axial loads (Figs 8a to 8c). L was also more important than D in reducing cancellous bone stress under buccolingual loads (Fig 8e). On the other hand, D was found to be more important in reducing the cortical bone stress and enhancing the implant stability under buccolingual loads (Figs 8d and 8f).

Conclusions

From the biomechanical perspective, data from this study suggest that:

- L favored stress distribution more than D both in jaw bones under an axial load and in cancellous bone under a buccolingual load.
- L significantly increased the implant stability of an axial load, while D greatly enhanced that of the buccolingual load.
- D exceeding 4.0 mm and L over 11.0 mm are the best combination for optimal biomechanical properties in immediate loading implants in the type B/2 bone.

Different from osseointegrated implants, D and L are both important factors in reducing jaw bone stress and enhancing implant stability in type B/2 bone for the immediate loading of implants

Limitations of this study could result from the assumptions made on the properties of the materials and the simplification of the models in the finite element analysis. Nonetheless, these data will provide a valuable reference for clinical practices.

Acknowledgment

This work was supported by a grant from the National Natural Science Foundation of China (no. 30900284).

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Literature Abstract

Biosphosphonate-related osteonecrosis of the jaw and its associated risk factors: A Belgian case series

Biosphosphonate-related osteonecrosis of the jaw (BROJ) is a serious oral complication of bisphosphonate (BP) treatment involving the exposure of necrotic bone. BPs are widely used to inhibit osteoclastic activity in diseases characterized by excessive bone resorption and for prevention of metastases in cancer patients. The pathogenesis is unclear but may include alteration of angiogenesis. BPs are known to concentrate in the jaws due to the greater degree of vascularization and daily remodelation around the periodontal ligament of teeth. Different risk factors are involved, but the main one reported is dental extractions. In Belgium, 34 cases were retrospectively evaluated to identify potential risks factors. Treatment with BPs, exposed necrotic bone, and no history of radiation therapy to the jaws were required. The Fisher exact test was used to evaluate any possible influence of several binarized variables on the treatment outcomes. Twenty-three women and 11 men with an average age of 62 years were examined. Six percent of them were diabetic, 35% smokers, 17% consumed alcohol, 69% presented with poor oral hygiene, and 86% had undergone chemotherapy. Eighty-eight and a half percent of patients used BPs to manage disseminated cancers and 11.5% for osteoporosis. The most frequently used BP was zoledronic acid. The average time of BP treatment before any BROJ symptom was 35 months in cancer patients and 50 months in osteoporosis patients. Fifty percent of patients had undergone extractions and lesions were present at extraction sites. Biopsy of the affected area showed necrotic bone in 91% of patients. Antibiotic treatments and oral rinses were prescribed for more than 4 weeks, and 57% of patients were cured with complete remission of bone exposure with mucosal closure. Surgical treatment appears to be nonbeneficial since only 20% were completely cured. Presently, no clinical, biologic, or pharmacologic factors allow us to predict which patients taking BPs are at the greatest risk for developing BROJ. Smaller lesions presented better prognoses. Local treatments combined with long-term antibiotics are also correlated with better prognoses. Further studies should focus on the size of the lesion to evaluate its effects as a predicting risk factor. Finally, prevention is more important than treatment and the establishment of good oral hygiene and surgical procedures prior to the start of BP therapy are critical. Patients treated with BPs need to be aware of the complications that could occur in the jaws, especially in relation to dental extractions.

Saussez S, Javadian R, Hupin C, et al. *Laryngoscope* 2009;119:323–329. **References:** 26. **Reprints:**Sven Saussez, MD, PhD, Laboratory of Anatomy, Faculty of Medicine and Pharmacy, University of Mons-Hainaut, Pentagone 1B-Avenue du Champ de Mars, 6, B-7000. Email: sven.saussez@umh.ac.be—*Luisa F. Echeto, Florida*