Load Transfer by an Implant in a Sinus-Grafted Maxillary Model

Mete I. Fanuscu, DDS[1]/Keisuke Iida, DDS, PhD[2]/Angelo A. Caputo, PhD[3]/Russell D. Nishimura, DDS[4]

Purpose: *This in vitro study determined the stress distribution around an implant placed in a posterior edentulous maxillary model with simulated sinus grafts that had different degrees of stiffness.* ***Materials and Methods:*** *The composite photoelastic model with a standard threaded implant consisted of simulated crestal cortical, cancellous, sinus cortical, and grafted bone. The graft maturation process and inherent graft quality were represented in the model by varying the stiffness of the graft. Prior to placement of the simulated graft, axial and inclined loads were applied to the implant. The stresses that developed in the supporting structures were analyzed photoelastically. The graft was then placed and the testing procedure was repeated over 4 consecutive days, during which time the simulated graft stiffened.* ***Results:*** *The stress analysis indicated that before placement of the simulated graft, loading on the implant transferred the highest stresses to cortical bone. The presence of the simulated graft transferred stress from the native bone simulants to the simulated grafted bone.* ***Discussion:*** *As the stiffness of the graft increased, a more equitable stress distribution was observed in the multilayer bone surrounding the implant.* ***Conclusion:*** *Loading of an implant in a less stiff grafted sinus could lead to overloading of the native bone as well as the maturing grafted bone.* INT J ORAL MAXILLOFAC IMPLANTS 2003;18:667–674

Key words: *bone graft, bone stiffness, dental implant, maxillary sinus augmentation, stress distribution*

Maxillary sinus bone graft augmentation has become one of the most common surgical procedures for increasing bone volume for implant placement in the posterior atrophic edentulous maxilla. Since introduction of the sinus graft technique by Boyne and James,[1] various graft materials, implants, and procedural modifications have been proposed to improve the efficacy of the therapy. Autogenous bone,[2–5] allogenic materials,[5,6] alloplastic materials,[5,7] xenogenic materials,[5,6] and combinations of these materials[4–6,8] have been utilized. Sinus grafting is usually considered for an atrophic maxilla, such as Class V and VI according to the classification of Cawood and Howell.[9] Average ridge heights of Classes V and VI jaws were reported to be 7.4 and 3.2 mm, respectively.[10]

The edentulous posterior maxilla is anatomically characterized by thin cortical bone at both the ridge crest and sinus floor and low-density cancellous bone in the remainder (Fig 1).[11] Depending on the preoperative bone level, simultaneous or delayed implant placement techniques have been employed in sinus graft procedures. In a consensus report, Jensen and coworkers stated a 90% success rate for implants in sinus grafts with at least 3 years of function.[5] The report included patients with simultaneous and delayed implant placement in various

[1]Assistant Professor and Director, Advanced Education in General Dentistry, Division of Restorative Dentistry, School of Dentistry, University of California at Los Angeles, Los Angeles, California.
[2]Research Fellow, Division of Advanced Prosthodontics, Biomaterials Science, and Hospital Dentistry, School of Dentistry, University of California at Los Angeles, Los Angeles, California.
[3]Professor, Division of Advanced Prosthodontics, Biomaterials Science, and Hospital Dentistry, School of Dentistry, University of California at Los Angeles, Los Angeles, California.
[4]Associate Professor, Division of Advanced Prosthodontics, Biomaterials Science, and Hospital Dentistry, School of Dentistry, University of California at Los Angeles, Los Angeles, California.

Reprint requests: Dr Mete I. Fanuscu, UCLA School of Dentistry, CHS 20-114, 10833 Le Conte Avenue, Los Angeles, CA 90095-1668. Fax: +310-794-7964. E-mail: mfanuscu@ucla.edu

Presented in part at the 78th General Session of the International Association for Dental Research, April 2000, Washington, DC.

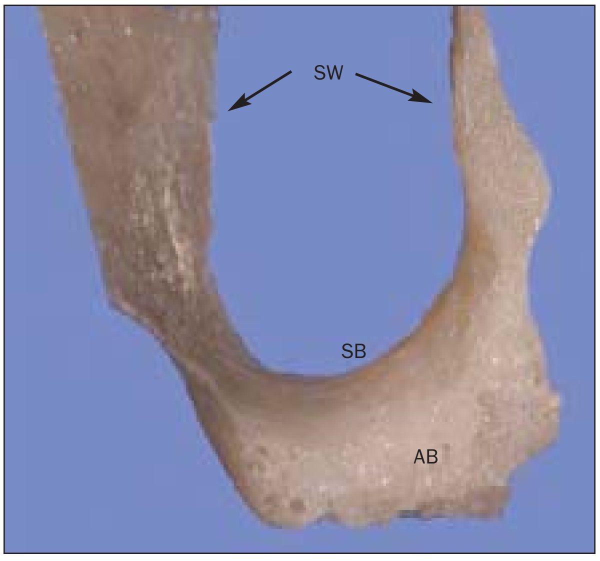


Fig 1 Cross-section of alveolar bone with sinus cavity and walls in the posterior maxilla from human cadaver. SW = sinus walls; SB = sinus bone; AB = alveolar bone.

grafts. There was no indication of the superiority of a particular protocol or material. However, there was a statistically significant difference in implant loss when available residual or native bone was 4 mm or less as opposed to 5 mm or greater.

A complex structure consisting of bone with varying stiffness can be found around implants placed in the posterior maxilla with grafted sinus(es). A crucial process that leads to the stability of osseointegrated implants is mineralization of the bone adjacent to the implant surface. Native bone, which is a critical factor in establishing and maintaining osseointegration, consists of crestal cortical bone, cancellous bone, and sinus floor cortical bone. The contribution of the grafted bone to the establishment and maintenance of implant stability is not yet understood. Load-bearing characteristics of grafted bone depend on the graft material and its maturation process. Several studies have investigated the total volume of hard tissue within various grafted sinuses to predict long-term implant stability. According to histologic analysis, the vital mineralized tissue volume of the grafted sinus ranged from 26% to 69% when only autogenous bone was used.[12–15] The range of vital mineralized tissue volume was 5% to 45% when any other graft material or combinations of materials were used.[8,12,16–18] It also should be noted that the mineralized tissue volume of grafted sinuses has been reported as relatively greater than that of native cancellous bone in the edentulous posterior maxilla, with mineralized tissue volume of the latter ranging from 17.1% to 26.7%.[19]

Premature loading and/or overloading might be significant concerns in sinus graft cases, since different graft materials and their maturation patterns can have variable load-bearing capacities. Biomechanically, control of the load transfer to bone surrounding the implants plays an important role in the long-term success of implant therapy.[20] Several studies have reported that appropriately controlled loads can stimulate bone remodeling around implants,[21,22] whereas excessive stresses cause marginal bone resorption.[23–25]

The purpose of this study was to investigate the stress distribution in bone around an implant placed in a posterior atrophic maxilla with a simulated sinus graft by use of a composite photoelastic model.

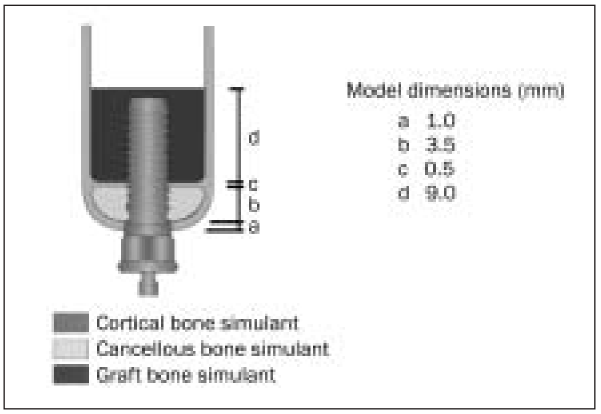
MATERIALS AND METHODS

A composite photoelastic model simulating a unilateral atrophic edentulous posterior maxilla was fabricated for quasi–3-dimensional testing and analysis (Fig 2a). Individual photoelastic simulants with different stiffnesses were used for cortical bone (PLM-1, Measurements Group, Raleigh, NC) and cancellous bone (PL-2, Measurements Group). Simulated crestal cortical bone, cancellous bone, and sinus floor cortical bone were fabricated in 1-mm, 3.5-mm, and 0.5-mm heights, respectively (Fig 2b). Therefore, the total height of simulated native bone was 5.0 mm.

A standard threaded implant, 3.75 mm in diameter and 13 mm in length (Implant Innovations, Palm Beach Gardens, FL), was incorporated into the model. Photoelastic resins representing the native bone components were poured directly around the implant and allowed to cure completely. An experimental photoelastic resin (modified PLM-1, Measurement Group) representing the graft was then placed into the simulated maxillary sinus cavity (Fig 2b). Several resin hardener ratios of PLM-1 were tested previously to establish a range of stiffness values. Beams of modified PLM-1, 4.5 × 2.8 × 30 mm, were tested in flexure on an Instron test machine (Instron, Canton, MA). Three beams of each formulation were tested at 3, 4, 5, 6, 7, and 10 days. From the results of these tests, a formulation with a change in stiffness over time was selected to simulate the mechanical response of either a bone graft maturing over time or of different qualities of graft materials (Fig 3).

Fig 2a (*Left*) Photoelastic model of the grafted posterior maxilla with an implant.

Fig 2b (*Below*) Schematic cross-section of the model showing the height of each simulant.



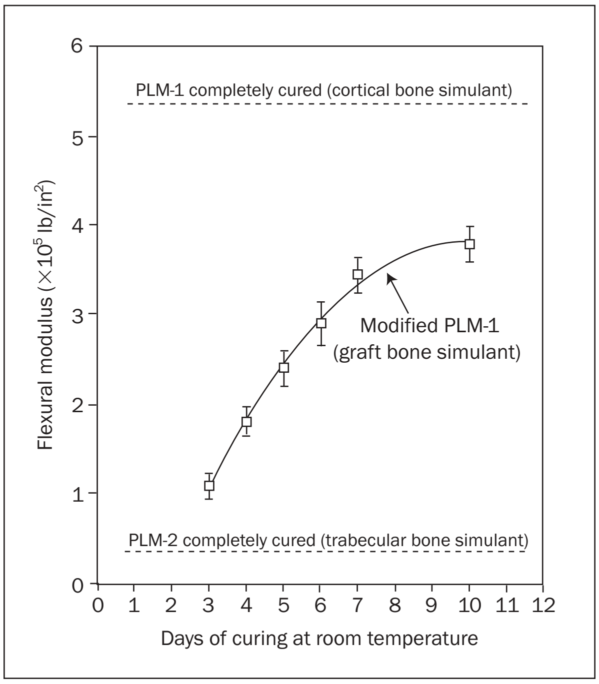
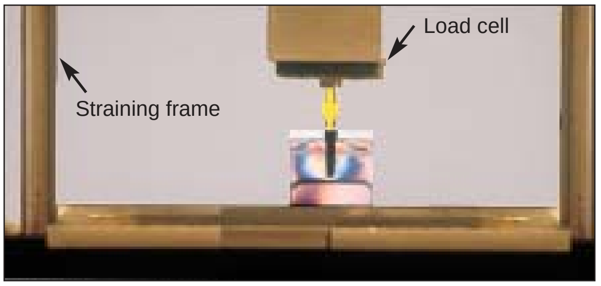


Fig 3 (*Left*) Stiffness values of the bone simulants. The grafted bone simulant became stiffer with aging.

Fig 4 (*Below*) Model under load in straining frame.



Axial loads were applied to the implant center through an implant mount (Implant Innovations) in a loading frame by means of a calibrated load cell mounted on the movable head of the frame. Loads were monitored and controlled by a digital readout (models 2130 and 2120A, Measurement Group) (Fig 4). Loads of 13.6 kg (30 lb) were applied because they are realistic functional levels and provide a satisfactory optical response within the model. To represent cantilevering forces, inclined loads of 13.6 kg were also applied while the model was tilted 15 degrees to the implant axis. The stresses that developed in the supporting structures were observed and recorded photographically in the field of a circular polariscope. To minimize surface refraction and facilitate photoelastic observation, the model was submerged in a tank of mineral oil during the analysis. The loading and recording sequences were performed before placement of the grafted bone simulant. After the graft was placed, the loading procedure was repeated at the predetermined days (3, 4, 5, and 6, which corresponded to the change in flexural modulus and represented the maturity and quality of grafted bone), to determine the effects of increasing stiffness on load transfer. Testing and recording procedures were repeated at least 2 times so that reproducibility of the technique could be verified. Photoelastic stress fringes that

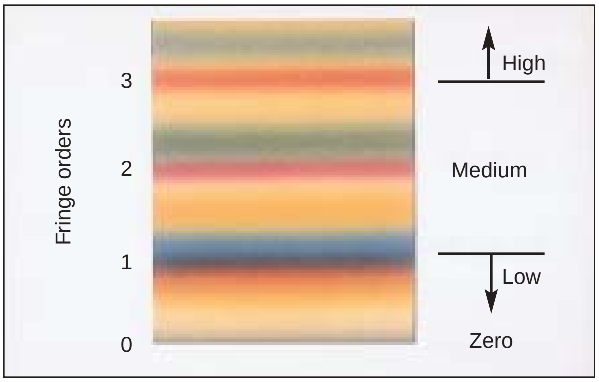


Fig 5 Relationship between stress level and fringe order used to describe results.

developed in the supporting structure were analyzed on the scanned data photographs, which were subsequently viewed with a computer graphic program (Photoshop 4.0; Adobe Systems, San Jose, CA) The stress intensity (number of fringes) and their locations were subjectively compared. In the interpretation of stress data, the following terminology was adopted (Fig 5): Low stress = 1 fringe or less; moderate stress = between 1 and 3 fringes; high stress = more than 3 fringes.

RESULTS

Photoelastic examination of the model before and after placement of the graft simulant revealed no significant initial stresses. This observation established that the isochromatic fringes produced upon loading were direct results of the applied loads. Further, no significant residual stresses were evident after any of the loading sequences.

Loading Before Graft Placement

Under axial loading, high-level stresses were observed in the crestal cortical bone simulant. Moderate stress was noted in cancellous and sinus floor cortical bone simulants (Figs 6a and 6b). With inclined loading, higher stresses occurred in all layers of the native bone simulants along the implant. The stress concentration in the cancellous bone was on the side away from the applied load (Figs 7a and 7b). In both loading conditions, low stress was observed in the cortical bone simulant at the sinus walls.

Loading After Graft Placement

With the presence of the graft and its increasing stiffness over time, stress distribution patterns changed in bone simulants surrounding the implant. With the implant subjected to axial loading when the simulated graft was at its most flexible stage, the distribution of stress within the native bone simulants was similar to that observed before placement of the graft, but of a lower intensity (Figs 8a and 8b). Further, mild stress developed around the apical portion of the implant in the graft. Under inclined loads, the intensity of stress in the native bone simulants was notably higher than that in the graft simulant (Figs 9a and 9b). As the stiffness of the simulated graft gradually increased, the graft assumed a greater proportion of the load, with concomitant stress reduction in the native bone simulants. When the graft achieved its highest stiffness, and when it was loaded axially, moderate level stresses were observed in all bone simulants (Figs 10a and 10b). When the graft was at its stiffest stage and inclined load was applied, moderate stresses were concentrated around the crestal and sinus cortical bone, as well as the apical portion of the implant (Figs 11a and 11b).

DISCUSSION

Short-term clinical data suggest promising outcomes in sinus-grafted implant cases. However, a better understanding of implant biomechanics in this anatomy would perhaps result in better treatment planning and outcomes. A multilayer bone structure surrounds implants in the posterior maxilla with an augmented sinus. In an attempt to mimic this complex structure, a dimensionally similar model was fabricated with photoelastic resins with different stiffnesses. The elastic modulus of oral bone and grafts is not well known; however, substantial differences in stiffness values have been indicated among them (Table 1).[26,27]

Two photoelastic resins, with an over tenfold difference in elastic modulus, and a modified resin whose elastic modulus ranged within that difference were employed in this study. It should be noted that stiffness of the grafted sinus could be lower or higher than that of the cancellous bone, depending on the graft material and maturation process. The present study assumed the stiffness of the graft to be greater in light of the available literature. Simion and coworkers demonstrated a direct correlation between the density of pre-existing bone and the density of regenerated bone.[28] A graft in the sinus might assume the mechanical characteristics of sinus cortical bone. In addition, the volume of vital mineralized tissue in the grafted sinus has been shown to be consistently greater than that of cancellous bone, especially when autogenous bone is used.[19] This larger volume of mineralized tissue in

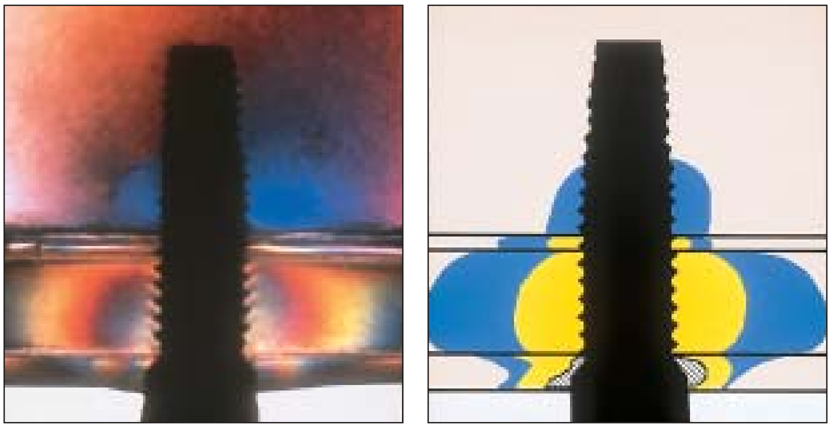
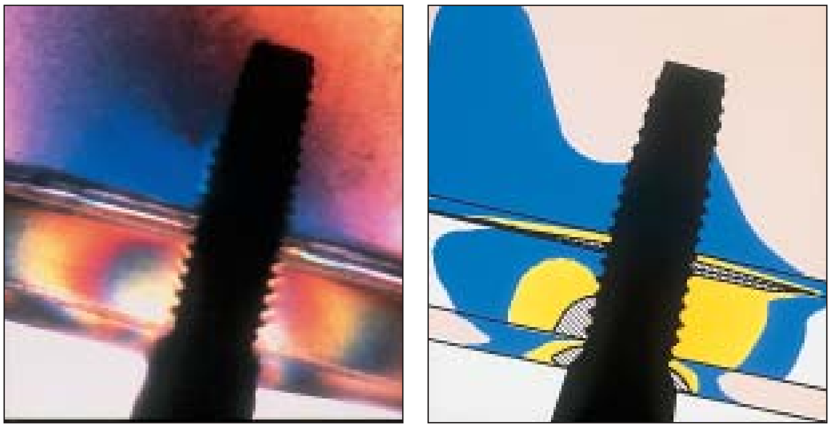
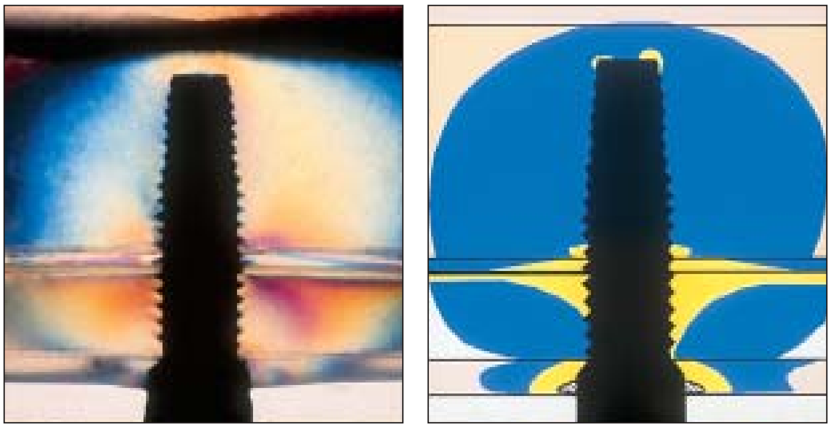


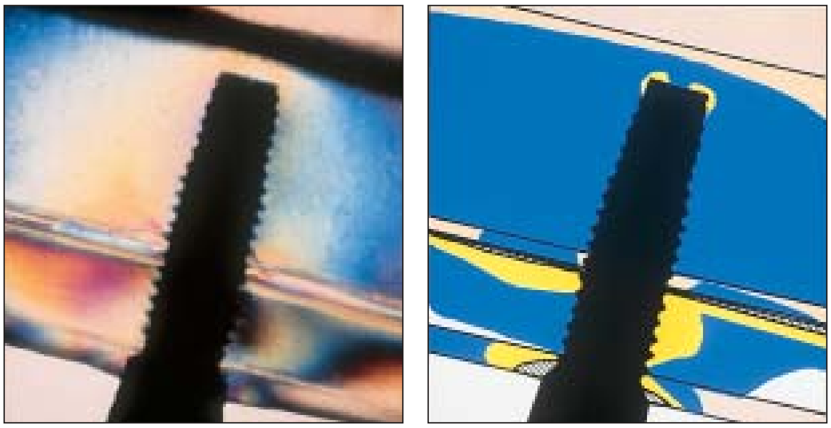
Fig 6a and 6b Stresses produced in the model under 13.6-kg axial load without simulated graft. *(Left)* Isochromatic fringe patterns; *(right)* diagrammatic representations of stress intensities. Stress distribution areas use blue for low-level stress, yellow for moderate stress, and cross hatching for high-level stresses.



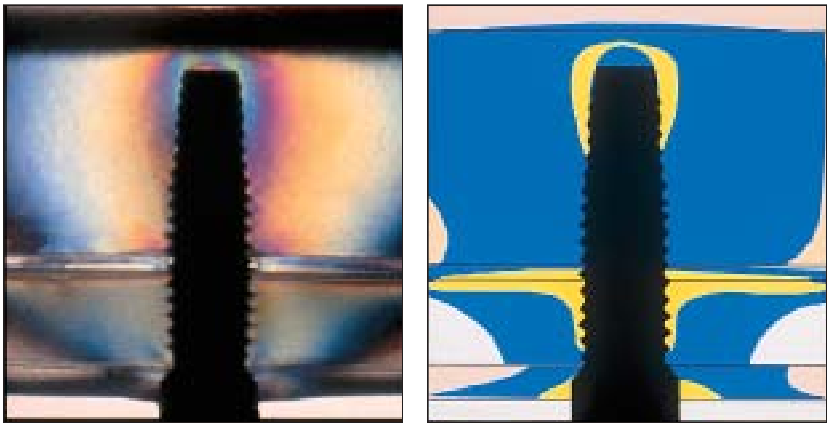
Figs 7a and 7b Stresses produced in model under 13.6-kg inclined load without simulated graft. *(Left)* Isochromatic fringe patterns; *(right)* diagrammatic representations of stress intensities.



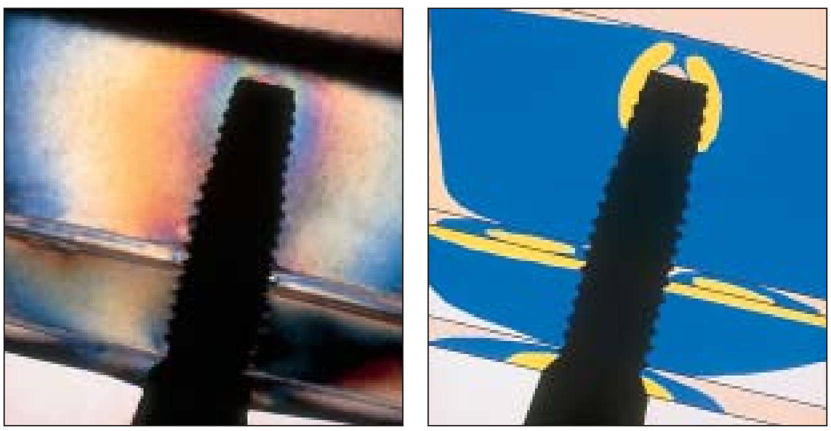
Figs 8a and 8b Stresses produced in model under 13.6-kg axial load with simulated graft in its least stiff stage. *(Left)* Isochromatic fringe patterns; *(right)* diagrammatic representations of stress intensities.



Figs 9a and 9b Stresses produced in model under 13.6-kg inclined load with simulated graft in its least stiff stage. *(Left)* Isochromatic fringe patterns; *(right)* diagrammatic representations of stress intensities.



Figs 10a and 10b Stresses produced in model under 13.6-kg axial load when the stiffness of the simulated graft increased to its highest level. *(Left)* Isochromatic fringe patterns; *(right)* diagrammatic representations of stress intensities.



Figs 11a and 11b Stresses produced in model under 13.6-kg inclined load when the stiffness of the simulated graft increased to its highest level. *(Left)* Isochromatic fringe patterns; *(right)* diagrammatic representations of stress intensities.

Table 1 Elastic Modulus of Tissues[26,27] and Simulants

Bone	Elastic modulus (GPa)	Simulant	Elastic modulus (GPa)
Cortical	14	PLM-1	2.93
Cancellous	1.4	PL-2	0.21
Grafted	up to 11	Modified PLM-1	Variable*

*Value varies with age.

grafted material is potentially indicative of higher stiffness. Even though conclusive evidence concerning the relative mechanical characteristics of graft and cancellous bone is lacking, this study provides an initial attempt at demonstrating the interactions of different quality bones with the loaded implant. Further studies utilizing a more flexible graft simulant are currently in progress.

Photoelastic modeling, like all in vitro studies that use model systems, has advantages and limitations. The most advantageous point of this technique in comparison with other methods, such as finite element analysis, is the use of actual materials such as implants. On the other hand, as a disadvantage of this technique, it is currently difficult to adjust the degree of osseointegration. A few studies have been carried out on bone-implant contact using retrieved titanium microimplants from the human posterior maxilla with grafted sinuses.[19,29] They revealed less bone-implant contact area in the grafted bone portion, particularly for implants placed simultaneously with a bone graft, than in the native bone portion. Although there is no evidence of a relationship between the degree of bone-implant contact and stress distribution, it can be hypothesized that potentially much higher magnitudes of stress might concentrate in the native bone/implant interface when the interface of the implant with grafted bone is diminished. In the photoelastic model, the implant was completely osseointegrated in both native and grafted bone simulants; the magnitude of stresses might be different in the clinical situation. However, the trends of stress distribution would not be substantially changed. These trends were effectively demonstrated in the complex model under axial and inclined loads.

The results of this study indicated that higher stresses occurred in the stiffer bone simulants around the implant, and the direction of the inclined load affected the localization of stresses. The stress was concentrated at the cortical bone when the grafted bone had a low stiffness value. However, some portions of the high-level stresses were transferred to the graft material around the apical portion of the implant when the stiffness value of the grafted bone approximated that of cortical bone. Several in vivo studies have demonstrated that excessive marginal bone loss in the cortical bone around implants was associated with occlusal overloads.[20–22] These studies indicated that the crestal cortical bone around implants was most likely subjected to an excessive concentration of stress. Therefore, safe loading of an implant is a critical matter, especially when the implant is partially supported by a graft. The graft simulant in this study had stiffened over time, and the implant was loaded on 4 consecutive days to demonstrate changes taking place in the supporting structure. According to the findings of the present study, it is suggested that loading an implant in poor quality bone and/or a premature graft in the sinus might cause increased stress concentration in the native bone, especially around the coronal portion of the implant. Subsequently, marginal bone resorption might be provoked, if the load-bearing capacity of bone is surpassed. This may explain the decreased success rates that result when implants are placed in posterior sites with less than 5 mm of bone in combination with sinus grafts.[5]

Mineralized tissue quality of the grafted sinus is dependent on the type and maturity of the graft material.[8,10–13,19] Rangert and associates reported that the loading capacity of grafted bone in the maxillary sinus was lower than that of native bone in the posterior edentulous maxilla during the healing period.[30] Ellegaard and colleagues placed implants into a minimum 3 mm of alveolar bone and protruded the implants more than 5 mm into the maxillary sinus, without bone grafts.[31] The results of that study showed that the success rate of sinus-penetrating implants was reduced by half when grafts were not used, and marginal bone loss was greater than 1.5 mm. However, according to the findings of the current study, with better quality and/or mature grafted bone, some of the high-level stresses might be transferred to the graft, and, as a result, concomitant stress reduction in the native bone could take place. This process could lead to a more equitable stress distribution in the multilayer bone surrounding the implant.

CONCLUSIONS

This in vitro study determined the stress distribution around an implant placed in a composite photoelastic model of a posterior edentulous maxilla with a simulated sinus graft.

1. In general, higher stresses were concentrated in the stiffer portions of the bone simulants under both axial and inclined loads before and after placement of the graft simulant.
2. Axial and inclined loads transferred low-level stresses to the cancellous bone and graft bone simulants when the grafted bone simulant was in its least stiff stage, representing a poor quality and/or premature graft.
3. As the stiffness of the graft increased, the graft assumed a greater proportion of the load, with a concomitant stress reduction in the native bone simulants.

These results suggest that the quality of a sinus graft can be critical to avoid overloading of native bone during function.

REFERENCES

1. Boyne PJ, James RA. Grafting of maxillary sinus floor with autogenous marrow and bone. J Oral Surg 1980;38:613–618.
2. Kent JN, Block MS. Simultaneous maxillary sinus floor bone grafting and placement of hydroxyapatite-coated implants. J Oral Maxillofac Surg 1989;47:238–242.
3. Blomqvist JE, Alberius P, Isaksson S. Two-stage sinus reconstruction with endosseous implants: A prospective study. Int J Oral Maxillofac Implants 1998;13:758–766.
4. Watzek G, Weber R, Bernhart T, Ulm C, Haas R. Treatment of patients with extreme maxillary atrophy using sinus floor augmentation and implants: Preliminary results. Int J Oral Maxillofac Surg 1998;27:428–434.
5. Jensen OT, Shulman LB, Block MS, Iacono VJ. Report of the Sinus Consensus Conference of 1996. Int J Oral Maxillofac Implants 1998;13(suppl):758–766.
6. Fugazzotto PA, Vlassis J. Long-term success of sinus augmentation using various surgical approaches and grafting materials. Int J Oral Maxillofac Implants 1998;13:52–58.
7. Wheeler SL, Holmes RE, Calhoun CJ. Six-year clinical and histologic study of sinus-lift grafts. Int J Oral Maxillofac Implants 1996;11:26–34.
8. Valentini P, Abensur D. Maxillary sinus floor elevation for implant placement with demineralized freeze-dried bone and bovine bone (Bio-Oss): A clinical study of 20 patients. Int J Periodontics Restorative Dent 1997;17:233–241.
9. Cawood JI, Howell RA. A classification of the edentulous jaws. Int J Oral Maxillofac Surg 1988;17:232–236.
10. Ulm CW, Solar P, Gsellmann B, Matejka M, Watzek G. The edentulous maxillary alveolar process in the region of the maxillary sinus: A study of physiological dimensions. Int J Oral Maxillofac Surg 1995;24:279–282.

11. Friberg B, Sennerby L, Roos J, Lekholm U. Identification of bone quality in conjunction with insertion of titanium implants. Clin Oral Implants Res 1995;6:213–219.
12. Moy PK, Lundgren S, Holmes R. Maxillary sinus augmentation: Histomorphometric analysis of graft materials for maxillary sinus floor augmentation. J Oral Maxillofac Surg 1993; 51:857–862.
13. Lundgren S, Moy PK, Johansson C, Nilsson H. Augmentation of the maxillary sinus floor with particulated mandible: A histologic and histomorphometric study. Int J Oral Maxillofac Implants 1996;11:760–766.
14. Blomqvist JE, Alberius P, Isaksson S, Linde A, Obrant K. Importance of bone graft quality for implant integration after maxillary sinus reconstruction. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1998;86:268–274.
15. Lorenzetti M, Mozzati M, Campanino PP, Valente G. Bone augmentation of the inferior floor of the maxillary sinus with autogenous bone or composite bone grafts: A histologic-histomorphometric preliminary report. Int J Oral Maxillofac Implants 1998;13:69–76.
16. Wheeler SL. Sinus augmentation for dental implants: The use of alloplastic materials. J Oral Maxillofac Surg 1997;55: 1287–1293.
17. Hanisch O, Lozada JL, Holmes RE, Calhoun CJ, Kan JYK, Spiekermann H. Maxillary sinus augmentation prior to placement of endosseous implants: A histomorphometric analysis. Int J Oral Maxillofac Implants 1999;14:329–336.
18. Froum SJ, Tarnow DP, Wallace SS, Rohrer MD, Cho SC. Sinus floor elevation using anorganic bovine bone matrix (osteograf) with and without autogenous bone: A clinical histologic, radiographic, and histomorphometric analysis—Part 2 of an ongoing prospective study. Int J Periodontics Restorative Dent 1998;18:529–543.
19. Watzek G, Ulm CW, Haas R. Anatomic and physiologic fundamentals of sinus floor augmentation. In: Jensen OT (ed). The Sinus Bone Graft. Chicago: Quintessence, 1999: 31–47.
20. Esposito M, Hirsch JM, Lekholm U, Thomsen P. Biological factors contributing to failures of osseointegrated oral implants (II). Etiopathogenesis. Eur J Oral Sci 1998;106: 721–764.
21. Adell R, Lekholm U, Rockler B, et al. Marginal tissue reactions at osseointegrated titanium fixtures (I). A 3-year longitudinal prospective study. Int J Oral Maxillofac Surg 1986; 15:39–52.
22. Sennerby L, Lundgren S. Histologic aspects of simultaneous implant and graft placement. In: Jensen OT (ed). The Sinus Bone Graft. Chicago: Quintessence, 1999:95–105.
23. Lindquist LW, Rockler B, Carlsson GE. Bone resorption around fixtures in edentulous patients treated with mandibular fixed tissue-integrated prostheses. J Prosthet Dent 1988; 59:59–63.
24. Quirynen M, Naert I, van Steenberghe D. Fixture design and overload influence marginal bone loss and fixture success in the Brånemark System. Clin Oral Implants Res 1992; 3:104–111.
25. Isidor F. Loss of osseointegration caused by occlusal load of oral implants. Clin Oral Implants Res 1996;7:143–152.
26. Spector M. Basic principles of tissue engineering. In: Lynch SE, Genco RJ, Marx RE (eds). Tissue Engineering: Applications in Maxillofacial Surgery and Periodontics. Chicago: Quintessence, 1999:3–16.
27. Moroi HH, Okimoto K, Moroi R, Terada Y. Numeric approach to the biomechanical analysis of thermal effects in coated implants. Int J Prosthodont 1993;6(6):564–572.
28. Simion M, Jovanovic SA, Trisi P, Scarano A, Piatelli A. Vertical ridge augmentation around dental implants using a membrane technique and autogenous bone or allografts in humans. Int J Periodontics Restorative Dent 1998;18(1):9–23.
29. Jensen OT, Sennerby L. Histologic analysis of clinically retrieved titanium microimplants placed in conjunction with maxillary sinus floor augmentation. Int J Oral Maxillofac Implants 1998;13:513–521.
30. Rangert B, Sennerby L, Nilson H. Load factor analysis for implants in the resorbed posterior maxilla. In: Jensen OT (ed). The Sinus Bone Graft. Chicago: Quintessence, 1999: 167–176.
31. Ellegaard B, Petersen JK, Baelum V. Implant therapy involving maxillary sinus lift in periodontally compromised patients. Clin Oral Implants Res 1997;8:305–315.