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Original Article

Biomechanical analysis of influence of implant configuration and bone quality on implant stability in augmented posterior maxilla

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Abstract: The present study applied FE methods to evaluate the biomechanical effects induced by implant configuration and bone quality within an augmented posterior maxilla. The aim of this study was to ascertain the optimal choice of implant on the basis of actual bone conditions. A couple of simplified maxillary segment models vary in bone quality (D2, D3 and D4 type) were constructed. Imlants were embedded into the atrophic posterior maxilla with only 8 mm residual bone height (RBH). An oblique force of 150 N was applied to the occlusal surface of implant and maximal equivalent von-Mises (EQV) stress was evaluated. The standard implant with its apical part embedded in high-stiffness graft exhibited the best stress distribution pattern among all groups. The short wide implant could also realize a desirable stress allocation similar to high-stiffness group in D2 and D3 bone. Stress in supporting bone increased concomitantly with the reduction of bone quality. Short wide implant could realize a desirable stress distribution when bone quality was preferable. Bone quality should be one of the crucial factors taken into consideration before implant placement. Grafted maxillary sinus augmentation was more recommended for implant rehabilitation in maxilla with poor quality.

Keywords: Alveolar bone atrophy, dental implants, bone substitutes, maxillary sinus floor augmentation, finite element analysis

Introduction

By the past decades, with a dependable effect of restoring the function and configuration of missing teeth, dental implant has been quite popular in daily clinic practice. Though the long-term success rate of dental implant has been pretty desirable, occasional failures do occur and disappoint clinicians anyhow. In consideration of the existence of different anatomical variation and insufficient residual bone, it becomes tougher to achieve a satisfactory long-time stability in the posterior maxilla than other regions [1].

To settle the matter, maxillary sinus augmentation was thought to be a predictable surgical technique to regain vertical bone height of atrophic posterior maxilla, which offered an ideal model to investigate healing events following bone grafting [2, 3]. Various clinical studies adopted non-grafted technique to increase the alveolar bone height under maxillary sinus [4] or used graft materials to optimize the configuration of residual bone [5] before implant placement. Sinus augmentation applying graft enabled a longer implant and boosted the success rate by increasing the bone-to-implant contact [6]. Note worthily, Huang [7] demonstrated that increasing stiffness of graft resulted in declining peak bone stress and hence the loading capability of graft was enhanced. However, the necessity of using graft in augmented sinus floor has been queried recently. Winter [8] reported a series of successful cases adopting a surgical technique called localized management of the sinus floor (LMSF) suggested by Bruschi [9], A systematic review asserted that no significant differences lying in implant success rate between sinus augmentation surgery with and without using any graft materials [10]. Thus whether to use graft materials needs to be further validated.

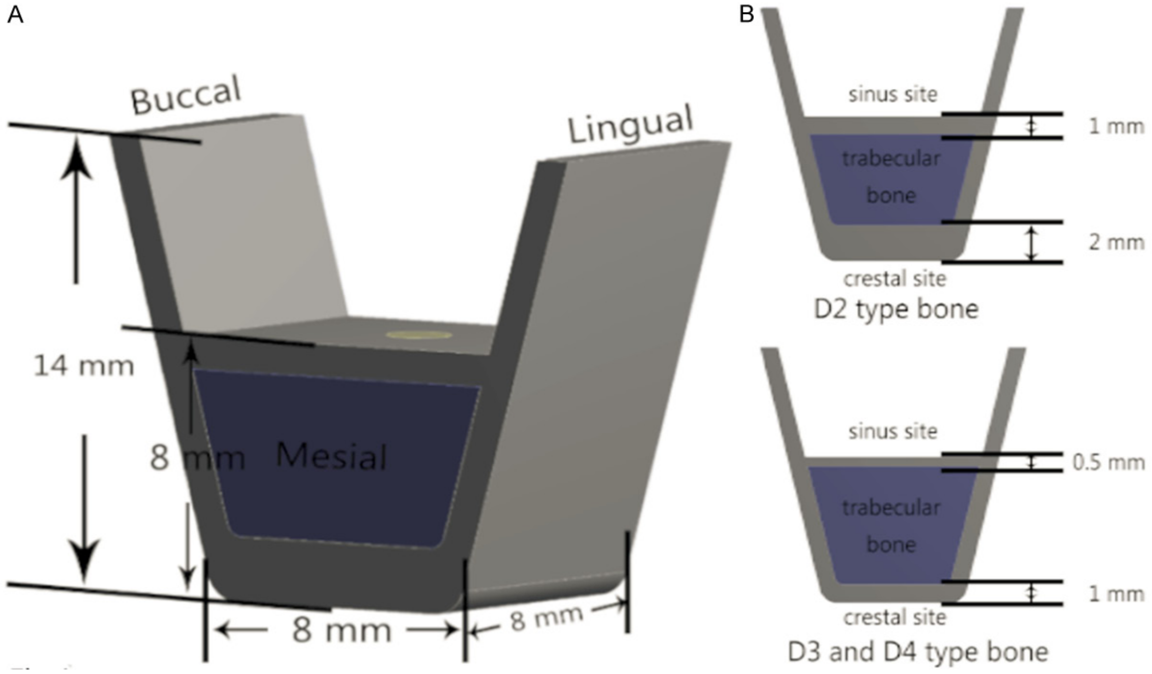

Figure 1. Simplified maxillary segment model vary in bone quality. A. A simplified maxillary segment model was designed to restore the structure of the atrophic posterior maxilla. The overall height, buccolingual and mesiodistal distance were 14 mm, 8 mm, 8 mm respectively. Residual bone height was 8 mm. B. D2 type bone: 2 mm in crestal cortical bone and 1 mm in sinus cortical bone, a core of dense trabecular bone; D3 and D4 type bone: 1 mm in crestal cortical bone and 0.5 mm in sinus cortical bone, D3 was a core of dense trabecular bone, D4 trabecular bone was low-density.

To achieve an ideal osseointegration in the bone-implant interface, not only adequate bone quantity is needed, but also satisfying bone quality is required. Bone quality could even be a key factor in determining optimal implant, initial stability and loading time. Misch [11] and Jaffin [12] stated that a high bone density provided implants with solid support during healing period as well as enabled better stress distribution and transmission in bone-implant interface. It was well documented that increasing failure rate tended to occur in poor quality sites [13].

However, bone quality and quantity are given factors, which cannot be altered easily. With the restrictions of poor conditions of local alveolar bone, the short wide implants seem to be a rational option instead of sinus augmentation [14]. A retrospective study [15] manifested that applying short wide implant in an atrophic maxilla with limited height but sufficient width was a feasible optional treatment. Moreover, the short wide implant could simplify surgical procedures for doctors. Despite of all these advantages, it remains unclear that whether a short wide implant could accomplish similar biomechanical characteristics as standard implants did in augmented maxilla.

3D FE analysis has been proven to be a superior tool for predicting unknown or intricate biological systems by offering an intuitional insight into the biomechanical environment [16]. Premised on designing accurately and analyzing appropriately, FE analysis can yield desirable outcomes extremely similar to the actual situations. Thus FE analysis was adopted in present study to compare biomechanical effects of short wide implant with that of standard implant adopting different maxillary sinus augmentation approaches within the posterior maxilla varying in bone quality. The aim of this study was to ascertain the optimal choice of implant when confronting complicate clinical situations.

Materials and methods

FE models

A 3D finite element model of maxillary segment with a missing first molar was established in present study. The overall height was 14 mm,

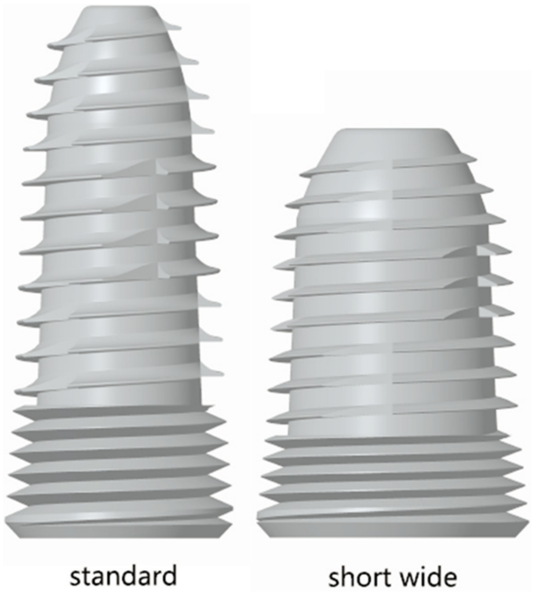

Figure 2. Implant model. The standard implant was 10 mm in length and 4.5 mm in diameter. The short wide implant was derived from standard implant with 8 mm in length and 5.5 mm in diameter.

Table 1. Elastic properties of materials modeled

Material	Young's modulus, E (GPa)	Poisson's ration, v
Cortical bone	13.7	0.3
Trabecular bone (D2 & D3)	1.37	0.3
Trabecular bone (D4)	0.231	0.3
High-stiffness Graft	11	0.3
Low-stiffness Graft	0.5	0.3
Titanium	110	0.35

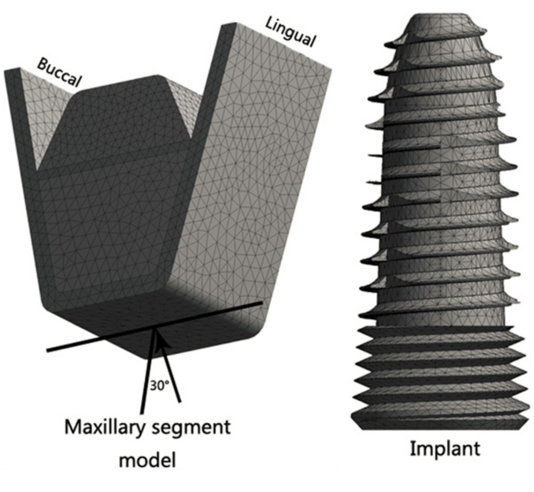

Figure 3. Meshed maxillary segment and implant models. The maxillary segment model and implant were meshed with 4-node tetrahedron elements. An oblique force of 150 N was applied to the implant at an inclination of 30° to the long axis of implant and toward buccal direction.

the buccolingual and mesiodistal distance were 8 mm. The maxillary segment was modeled with 8 mm in residual bone height (**Figure 1A**), possessing three distinctly different bone qualities (D2, D3, D4) according to Lekholm and Zarb [17]. D2 bone was composed of a core of dense trabecular bone surrounded by a thick layer of compact bone (2 mm in crestal cortex and 1 mm in sinus cortex); D3 bone was composed of a core of dense trabecular bone surrounded by a thin layer of compact bone (1 mm in crestal cortex and 0.5 mm in sinus cortex); D4 bone had a thin layer of compact bone surrounding a low-densing trabecular bone, whose structure is similar to that of D3 bone (**Figure 1B**). The model of implant (Neo CMI implant, IS 410, Neo Biotech, Korea) were duplicated from their original mechanical drawing measured by venier calipers. The standard implant had a total length of 10 mm and major diameter of 4.5 mm. The short wide implant was derived from standard implant with 8 mm in length and 5.5 mm in diameter (**Figure 2**).

Material properties

All corresponding modulus elasticity and Poisson's ratio of materials used in this study were determined from previous literatures [18-20] and summarized in **Table 1**. All the materials were assumed to be linear elastic, homogenous and isotropic [18, 19, 21]. Two distinct grafts were designed to stand for a wide spectrum of stiffness on purpose of achieving predictive accuracy. The high value was approximate to cortical bone and the low value was below the stiffness of trabecular bone. Implants were completely peri-implant packed by graft to represent an ideal situation suggested by Tepper [22].

Boundary conditions and loading

All FE models were generated by means of 0.7 mm tetrahedral elements and refinements were apllied to edges of interest (**Figure 3**). Models were divided into elements range from 161,000 to 467,000 and nodes vary from 258,000 to 667,000. Contact relationship between implant and adjacent bone was

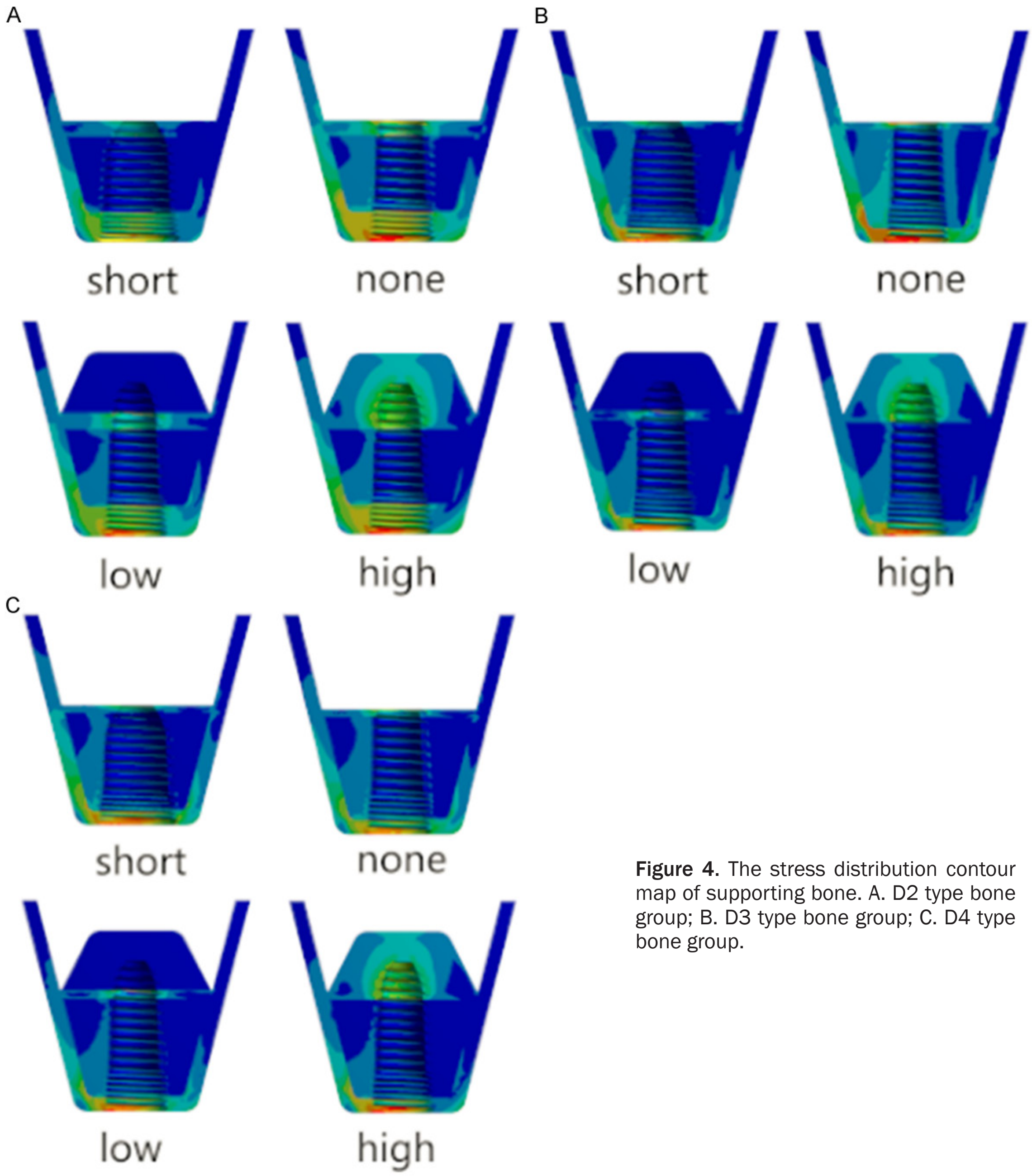

Figure 4. The stress distribution contour map of supporting bone. A. D2 type bone group; B. D3 type bone group; C. D4 type bone group.

defined as bonded to simulate the biomechanical environment. In order to simulate the occlusal force in a realistic way, an oblique force of 150 N [23, 24] was applied to the implant at an inclination of 30° to the long axis of implant (**Figure 3**). Mesial and distal surface of the maxillary segment were constrained without displacement in all directions. Maximal EQV stress was designed to evaluate the biomechanical effects of implants in the posterior maxilla vary in bone quality. In order to make it convenient for comparative analysis, we marked each group with a word. Short denoted short wide implant, none denoted sinus augmentation without graft, high and low denoted high-stiffness and low-stiffness graft in augmented sinus respectively.

Results

Judging from the stress distribution contour map (**Figure 4**), the highest stress mainly concentrated on crestal cortical bone around implant neck, whereas stress in trabecular

Table 2. Maximal EQV Stress (MPa) in supporting bone

Group	D2	D3	D4
Short	14.638	17.131	33.126
None	16.675	25.71	47.154
Low	16.163	22.245	37.382
High	14.09	17.543	21.198

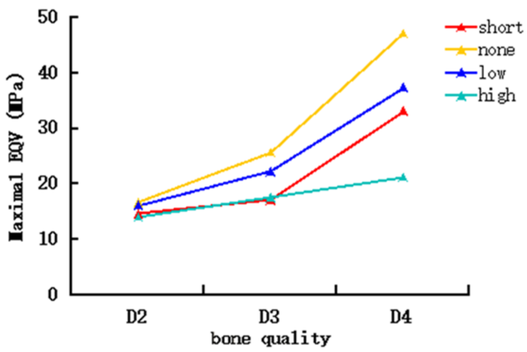

Figure 5. Trend chart of stress level change for each group.

bone was considerably low. **Table 2** presented the values of maximal EQV stress in supporting bone for each group. For D2 and D3 bone, the magnitude of maximal EQV stress in short wide implant group were quite close to high-stiffness group, whose stress distribution was second to none. So in biomechanical aspect, short wide implant seemed realized a desirable biomechanical characteristics in atrophic posterior maxilla with preferable bone quality.

D2 bone was able to allocate stress evenly on account of its thick layer of cortical bone. With the bone quality deteriorating, an escalating trend of stress in supporting bone emerged (**Figure 5**). The peak value of maximal EQV stress turned up in D4 bone, the poorest quality among all the levels of bone quality. Furthermore, the gap between groups tended to enlarge. As were shown in **Figure 5**, maxillary sinus augmentation without applying any graft generated the highest magnitude of stress. The existence of graft did reduce stress in supporting bone and the high-stiffness group performed better than low-stiffness group. For D4 bone, though the magnitude of stress induced by short wide implant was higher than high-stiffness group, it was still lower than the rest two groups.

Disscussion

Investigating the biomechanical effects resulted from bone quality and implant parameters by using clinical approaches solely would be insufficient. Adding the existence of maxillary sinus, examining biomechanical effects of implants in the posterior maxillary region became more complicate. For this reason, finite element analysis has been widely applied as a complementary method for exploring biomechanical phenomena in intricate biological tissues. Though previous studies provided clinicians with a large amount of practical information, few attempts had been made to elucidate the relationship between stress magnitude and implant configuration as well as bone quality in the atrophic posterior maxilla. Through this study, we had several interesting findings which might equip clinicians with some practical advice.

Marginal bone loss was an inevitable process after implant placement, which undermined the implant stability gradually [25]. Excessive bone load had been suggested one of the factors contributing to this process [26]. Van Steenberge [27] reported that marginal bone loss was up to 0.4 mm during the first year after implant placement and the annual loss reduced to 0.03 mm in the next two years. Yet the relationship between bone quality and MBL has not been well clarified so far and the present study tended to fill in this gap. Mechanical stress distribution primarily occurred to the bone-implant interface so that surrounding bone quality could influence stress distribution and transmission in a way. As was shown in the present study, D2 bone exerted more desirable stress distribution pattern than D3 and D4 bone. Analogy findings were validated by previous studies that cortical bone thickness played a vital role in implant stability [28, 29]. Bone tissue with a preferable quality could not only provide mechanical immobilization of implants [30], but also permit dispersing dense stress from implant to supporting bone [31]. Although D3 and D4 bone had the same bone configuration, the lower density of trabecular bone was unable to bear high stress, so that stress relocated from trabecular bone to cortical bone in D4 bone [32]. Chang suggested that the undesirable stress concentration in D4 bone would result in micromotion and initial instability [20].

In this case, bone quality should be taken into consideration in implant treatment plan.

Notably our study showed that stress mainly concentrated on the cortical bone around the neck of implant closet to the loading direction, irrespective of the surrounding bone quality or implant parameters. Such stress distribution pattern conformed to other studies investigating biomechanical behavior of implants [20, 33]. It was explained by that cortical bone possessed a higher elastic modulus and hence withstood more load than trabecular bone [20]. Remarkably, stress concentration tended to aggravate following deterioration of bone quality and the highest stress were occurred to D4 bone. Taking all these into accounted, poor bone quality would be one of the risk factors contributing to progressive marginal bone loss [33]. Then utilizing maxillary sinus augmentation to modify bone deficits before implant placement should be a necessary procedure in particular for the atrophic posterior maxilla with poor bone quality.

Deceasing residual bone height is the situation frequently encountered in posterior maxillary region. Applying graft materials in maxillary sinus augmentation had produced affirmative results and a mature graft would be an excellent option [34]. However, with the accumulation of successful cases adopting non-grafted sinus lifting technique [8, 35], sinus augmentation without grafts was proven to be a viable alternative when residual bone height was above 5 mm [4]. The present study revealed that graft markedly diminished stress in supporting bone and high-stiffness graft exhibited better performance. The capability of reducing stress was dramatically enhanced by improving graft stiffness, as was fairly pertinent to its mineralization degree [7]. With the reduction of bone density, an evident advantage of graft emerged in D3 and D4 bone. It seemed that graft could partly correct the unfavorable stress distribution induced by poor bone quality. In this regard, the ideal graft should have certain stiffness with the purpose of realizing preferable stress distribution.

Implant configuration, including diameter, length, played a crucial role in implant success rate [18]. Among these parameters, implant diameter was demonstrated to have larger influence on implant stability than length did [6]. A histologic study showed that wide implant possessed more contact area of implant-bone interface when comparing with standard implant [36]. This was confirmed by a FE analysis research of Qian, which manifested that a larger implant diameter reduced the maximal stress in supporting bone [37]. Li [18] declared that the short wide implant in a moderately atrophic maxilla appeared favourable when the diameter was above 5.0 mm. According to our study, short wide implant could achieve similar biomechanical effects as standard implant did with the help of high-stiffness graft under the condition of D2 and D3 bone. Quite a few clinical studies furnished evidence that clinical application of short wide implant had reached a desirable success rate [38, 39]. Therefore, short wide implant could be a feasible treatment when it came to absorbed maxilla possessing better bone quality. For D4 bone, the gap between short wide implant and high-stiffness graft arouse. It appeared that maxillary sinus augmentation in combination of high-stiffness graft was the first choice rather than short wide implant from the biomechanical view. Generally, although sinus augmentation utilizing high-stiffness graft performed better in stress characteristics, when taking treatment cost and duration into account, short wide implant might also be be a rational choice [40].

The 3D finite element models adopted in present study simulated the details of implant precisely. Several assumptions were made in material properties and boundary conditions to simplify the computational procedure. Given the limitations of this study, following conclusions might be reasonable:

1) Bone quality should be of particular concern when residual bone height is limited, as which had considerable impact on stress distribution in supporting bone; 2) Maxillary sinus augmentation with high-stiffness graft was recommended for implant rehabilitation in maxilla with poor quality from the biomechanical view purely; 3) With preferable bone quality, short wide implant could realize a desirable stress distribution and would be a rational option when residual bone height is limited.

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Disclosure of conflict of interest

None.

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