Stress Distribution on the Prosthetic Screws in the All-on-4 Concept: A Three-Dimensional Finite Element Analysis

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The all-on-4 concept, which is used to rehabilitate edentulous patients, can present with mechanical complications such as screw loosening and fracture. The purpose of this study was to evaluate the stress patterns induced in the prosthetic screws by the different prosthetic screw and abutment designs in the all-on-4 concept using finite element analysis. Von Mises stress values on 6 groups of each screw type, including short and narrow screw, short abutment; short and wide screw, short abutment; long and wide screw, short abutment; short and narrow screw, long abutment; short and wide screw, long abutment; and long and wide screw, long abutment, were compared under a cantilever loading of 200 N that was applied on the farther posterior to the position of the connection between the distal implant and the metal framework. Posterior prosthetic screws showed higher stress values than anterior prosthetic screws. The stress values in posterior prosthetic screws decreased as the length and diameter increased. In conclusion, the long and wide screw design offers advantages in stress distribution when compared with the short and narrow design.

Key Words: edentulous mouths, implant-supported dental prosthesis, screw loosening, all-on-4, finite element analysis

Introduction

Several prosthetic treatment options, such as complete dentures, removable implant-retained prostheses, and fixed implant-supported prostheses, exist for the rehabilitation of edentulous patients.[1] Implant-supported prostheses are indicated in edentulous patients who are uncomfortable with conventional dentures.[2] However, there are anatomic limitations such as a pneumatized maxillary sinus, proximity of the inferior alveolar canal, and resorption of the alveolar bone.[3,4] Thus, additional treatments such as bone augmentation and maxillary sinus elevation may be required for implant placement.[5–10]

In completely edentulous patients, these anatomical limitations can be overcome by using the all-on-4 concept without these additional treatments.[11] In this concept, 4 implants are placed; 2 of the anterior implants are placed straight, and 2 of the posterior implants are placed tilted in the anterior portion of the edentulous jaw to allow immediate insertion of the fixed prostheses.[12–14] Angled abutments are used in the posterior implants to create the path of the prostheses.[15,16] This concept provides the advantage of improved stress distribution with cross-arch stabilization, reduced cantilever, and placement of longer implants by distal tilting.[4]

However, clinical studies have shown mechanical complications such as prosthetic fracture and abutment or prosthetic screw loosening/fracture.[17–23] Prosthesis fracture can be resolved with prosthesis repair and occlusal adjustment,[24] and screw loosening can be resolved with retightening and occlusal adjustment.[15,18] However, removal of the remnant after screw fracture can sometimes damage the implant body.[25,26] Loosening of the screw causes poor fit of the superstructure and can lead to fracture of the screw or implant, damage or detachment of the superstructure, and resorption of the peri-implant bone.[27]

Studies on stress distribution using the all-on-4 concept were mostly related to implant fixture and peri-implant bone.[2,3,28–30] Studies on stress distribution of screws relating to screw loosening were only about the difference in stress distribution according to the angle of implant placement, abutment angle, and framework material.[31,32]

The design of the screw and abutment varies according to the manufacturing company. The aim of this study was to evaluate the stress distribution on the prosthetic screws while using different prosthetic screw lengths/diameters and abutment heights by the all-on-4 concept, using finite element analysis.

Materials and Methods

The 3-dimensional models of the Solidworks 2017 software were exported to Abaqus 2017 software for mesh generation, definition of material properties, boundary, and loading conditions. The tetrahedral elements (C3D4, a 4-node linear tetrahedron) used for mesh generation were adjusted for all

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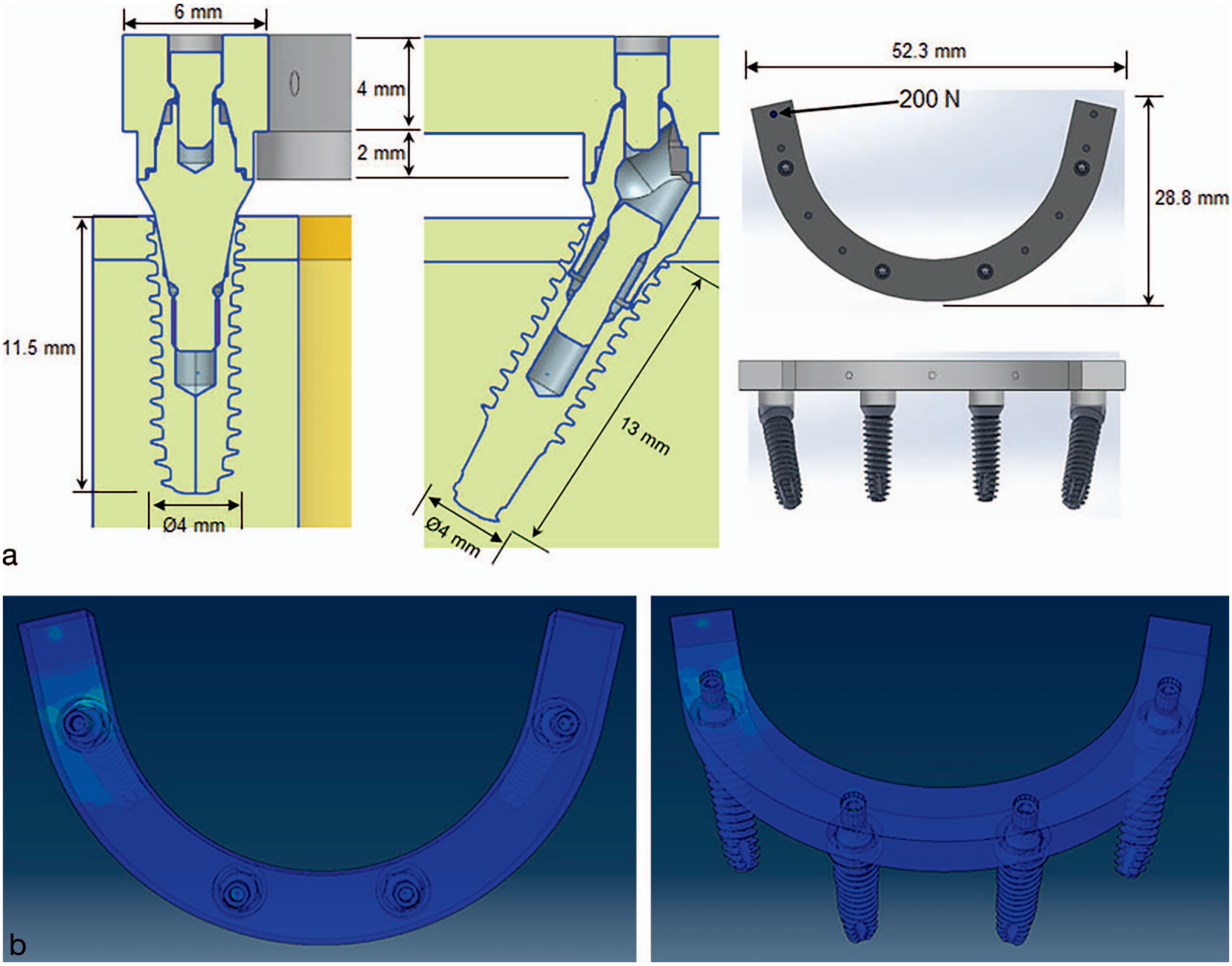

Figure 1. The design of the all-on-4 concept used in this study. (a) Drawing to represent the components of the finite element analysis. (b) Three-dimensional model in Abaqus software.

structures of minimum and maximum sizes (0.13–0.5 mm). Mesh refinement showed a relatively constant tendency below 0.2, and hence the mesh global seed size for prosthetic screws used in this study was 0.2. Meshes of 1074470 to 1104604 elements and 495462 to 511659 nodes were generated for the models. The integration point was 1 per element. The analytic thread option of a 60° thread angle was used.

Two mesial implants of 4-mm diameter and 11.5-mm length were placed bilaterally and vertically in the lateral incisor area, and 3 distal implants of 4-mm diameter and 13-mm length were placed bilaterally in the second premolar area with a 30° distal tilt, as shown in Figure 1.[31] To follow a path parallel to the straight multiunit abutment of the mesial implant, a 30° angled multiunit abutment was used for the distally tilted implant.

The abutments were connected to the fixtures, and the metal framework was connected to the abutments as shown in Figure 1. The metal framework with 6-mm width and height extended up to the first molar and had the form of an ideal arch made using an orthodontic arch wire that overlapped the margin of the abutment by 2 mm.[3,28,30]

The finite element analysis was performed in the 6 groups, each of different screw design, using the smeared simulation method. The smeared simulation method provides a threadlike simulation without using threads in the model, and the thread behavior is internally calculated based on thread definition parameters.[33] Stress distribution over the prosthetic screws on the loaded side was evaluated by applying a cantilever loading of 200 N in the first molar region of the metal framework[3,30] because, with implant-supported fixed prostheses, the average maximum occlusal force exerted by the first premolar and molars is approximately 200 N.[34] In Figure 1, a spot labeled 200 N indicates the cantilever area where the cantilever loading was applied. The cantilever area is farther posterior to the position of the connection between the distal implant and the metal framework. Its area was 0.79 mm^2. The loading was applied directly onto the metal framework.

The designs of the prosthetic screws and multiunit abutments used in this study are described in Figure 2. Each group was divided based on the designs of the prosthetic screw and the multiunit abutment: short and narrow screw, short abutment

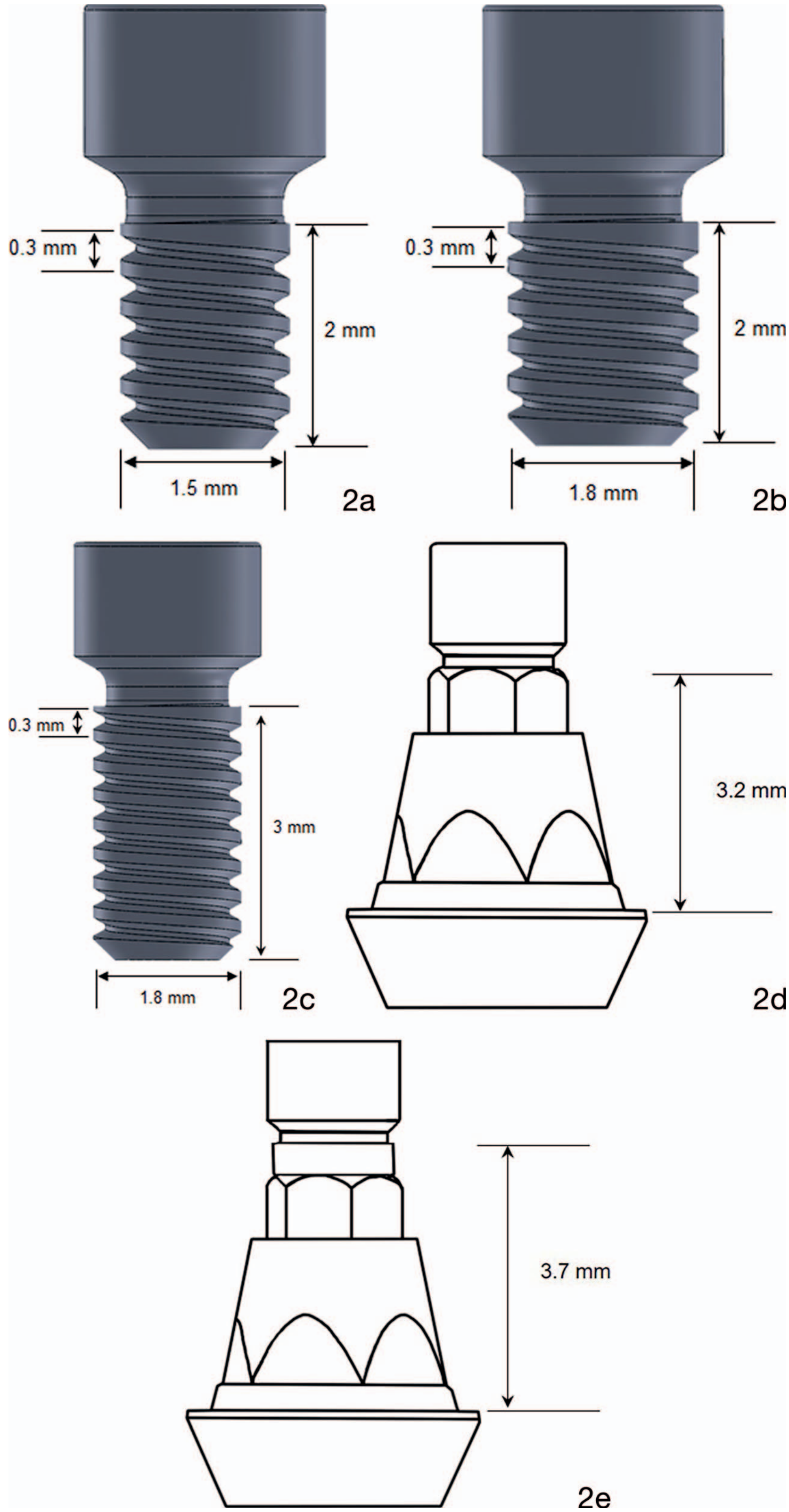

Figure 2. Designs of the prosthetic screws and multiunit abutments used in this study. (a) Short and narrow screw. (b) Short and wide screw. (c) Long and wide screw. (d) Short abutment. (e) Long abutment.

Table 1

Finite element analysis of mechanical properties*

Component	Material	Young's Modulus, MPa	Poisson Ratio
Fixture	Ti-Grade4	105 000	0.37
Screw	Ti-6AL-4V ELI	110 000	0.33
Abutment	Ti-6AL-4V ELI	110 000	0.33
Metal framework	Co-Cr alloy	218 000	0.33

*Ti indicates titanium; AL, aluminium; V, vanadium; ELI, extra-low interstitial; Co, cobalt; Cr, chromium.

group (SNS group); short and wide screw, short abutment group (SWS group); long and wide screw, short abutment group (LWS group); short and narrow screw, long abutment group (SNL group); short and wide screw, long abutment group (SWL group); and long and wide screw, long abutment group (LWL group; Figure 3). The length of the abutment was the measured distance from the center of the marginal plane of the abutment to the center of the top plane of the abutment.

Table 1 shows the mechanical properties such as type, Young's moduli, and Poisson ratios of the materials used in this study.[35–37] A boundary condition for the prosthetic and abutment screws was set to rotate around the axis of the screw so that no translational movement was possible. The whole model was set to have the same contact conditions, except the thread portion of the screw; the thread portion was made to have the bolt conditions of the half-thread angle, pitch, and diameter. The contact property was 0.5 of the friction coefficient in tangential behavior and 1 of the stiffness scale factor as penalty method in normal behavior.[38,39]

To determine the difference depending on the length of the prosthetic screw, the SWS and LWS groups and the SWL and LWL groups were compared. To determine the difference depending on the diameter of the prosthetic screws, the SNS and SWS groups and the SNL and SWL groups were compared. To determine the difference depending on the length of the abutments, the SNS and SNL groups, the SWS and SWL groups, and the LWS and LWL groups were compared. The bone-implant fixture interface was assumed to be completely fixed as if it were osseointegrated.

The results were visually transformed using colors ranging from blue to red, where red represented the highest stress value. The stress analysis was conducted using the von Mises stress value.

Table 3

Difference (%) between stress values observed on the posterior prosthetic screws of the loaded side by increasing the screw length/diameter and abutment height*

Modification	Before Increasing	After Increasing	Difference Between Values in the Posterior Prosthetic Screw, %
Length of screw	SWS group	LWS group	−4.1
	SWL group	LWL group	−8.7
Diameter of screw	SNS group	SWS group	−17.6
	SNL group	SWL group	−12.7
Height of abutment	SNS group	SNL group	−3.8
	SWS group	SWL group	+1.9
	LWS group	LWL group	−3.0

*SNS indicates short and narrow screw, short abutment; SWS, short and wide screw, short abutment; LWS, long and wide screw, short abutment; SNL, short and narrow screw, long abutment; SWL, short and wide screw, long abutment; LWL, long and wide screw, long abutment.

Results

The peak stress values observed on the anterior and posterior prosthetic screws of the loaded side in each group are described in Table 2. The difference between the stress values observed on the posterior prosthetic screws of the loaded side depending on the length and diameter of the prosthetic screw and height of abutment are described in Table 3. The stress patterns on the posterior prosthetic screws of the loaded side are shown in Figure 4 and those on the anterior prosthetic screws of the loaded side are shown in Figure 5.

The stress value in the posterior prosthetic screw was highest in the SNS group and lowest in the LWL group, whereas the anterior prosthetic screws showed similar stress distribution in all 6 groups. The anterior prosthetic screws showed lower stress values than the posterior prosthetic screws. The peak stresses in the posterior prosthetic screws are located at the lower thread area, whereas peak stresses in the anterior prosthetic screws are located around the shank.

The stress values in the posterior screws with short abutments was highest in the SNS group and lowest in the LWS group; it was highest in the SNL group and lowest in the LWL group with long abutments. Depending on the length of the screw, the peak stress on the posterior screws was 4.1% lower in the LWS group than in the SWS group and 8.7% lower in the LWL group than in the SWL group. Depending on the diameter of the screw, the peak stress on the posterior screws

Table 2

Peak stress values observed on the prosthetic screws of the loaded side in each group*

Peak Stress, MPa	SNS Group	SWS Group	LWS Group	SNL Group	SWL Group	LWL Group
Posterior prosthetic screw	246.1	202.9	194.6	236.7	206.7	188.7
Anterior prosthetic screw	159.2	155.0	170.6	136.3	147.0	160.6

*SNS indicates short and narrow screw, short abutment; SWS, short and wide screw, short abutment; LWS, long and wide screw, short abutment; SNL, short and narrow screw, long abutment; SWL, short and wide screw, long abutment; LWL, long and wide screw, long abutment.

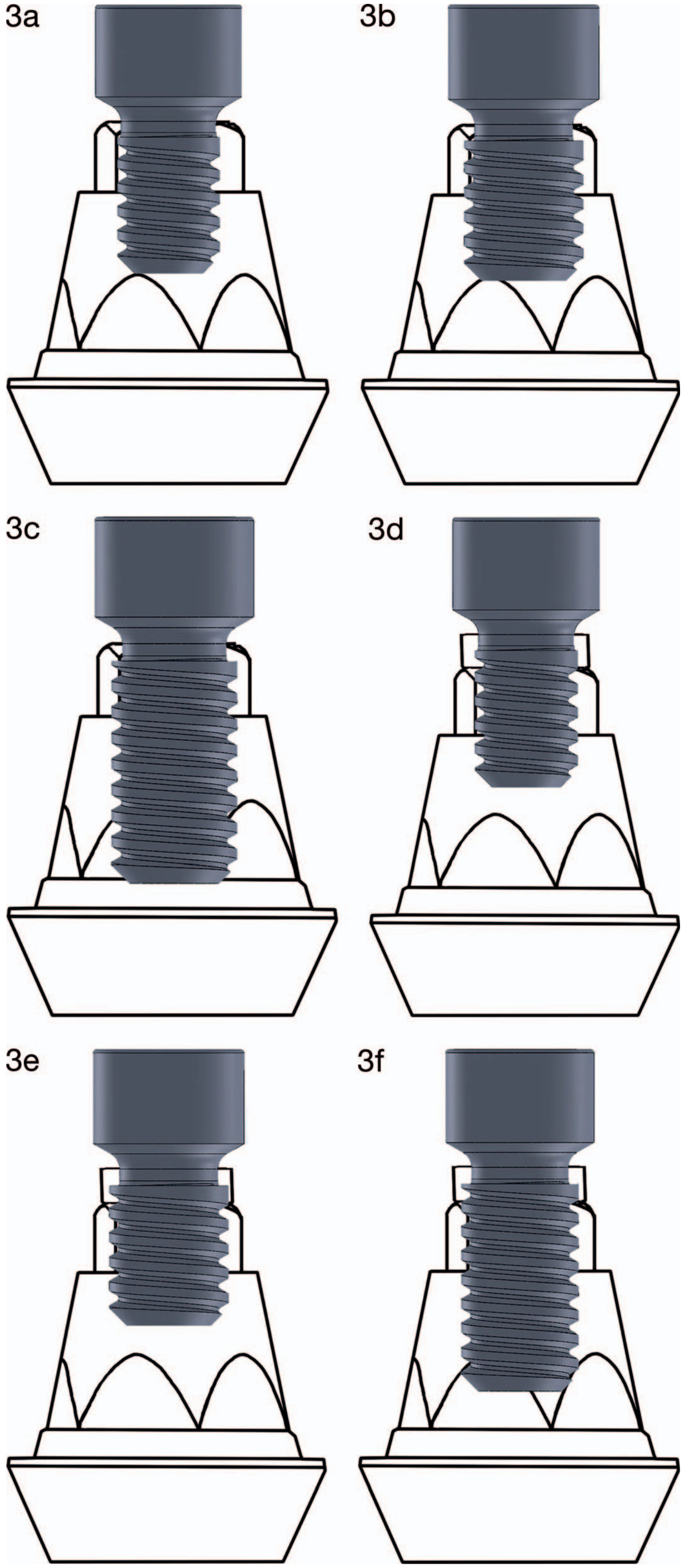

Figure 3. Schematic designs of screw and abutment in each group. (a) Short and narrow screw, short abutment group. (b) Short and wide screw, short abutment group. (c) Long and wide screw, short abutment group. (d) Short and narrow screw, long abutment group. (e) Short and wide screw, long abutment group. (f) Long and wide screw, long abutment group.

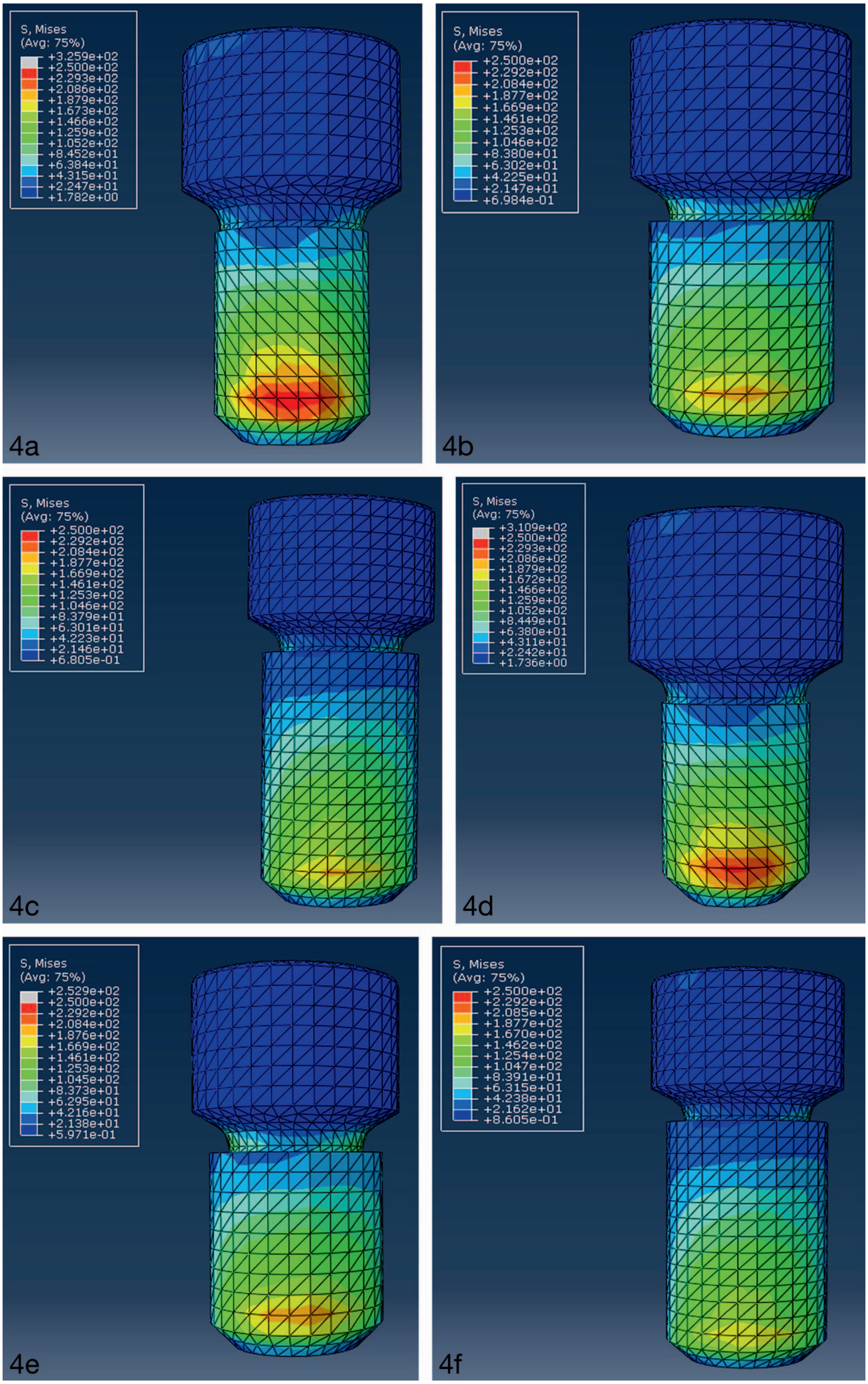

FIGURE 4. Stress distribution in the posterior prosthetic screw on the loaded side. (a) Short and narrow screw, short abutment group. (b) Short and wide screw, short abutment group. (c) Long and wide screw, short abutment group. (d) Short and narrow screw, long abutment group. (e) Short and wide screw, long abutment group. (f) Long and wide screw, long abutment group.

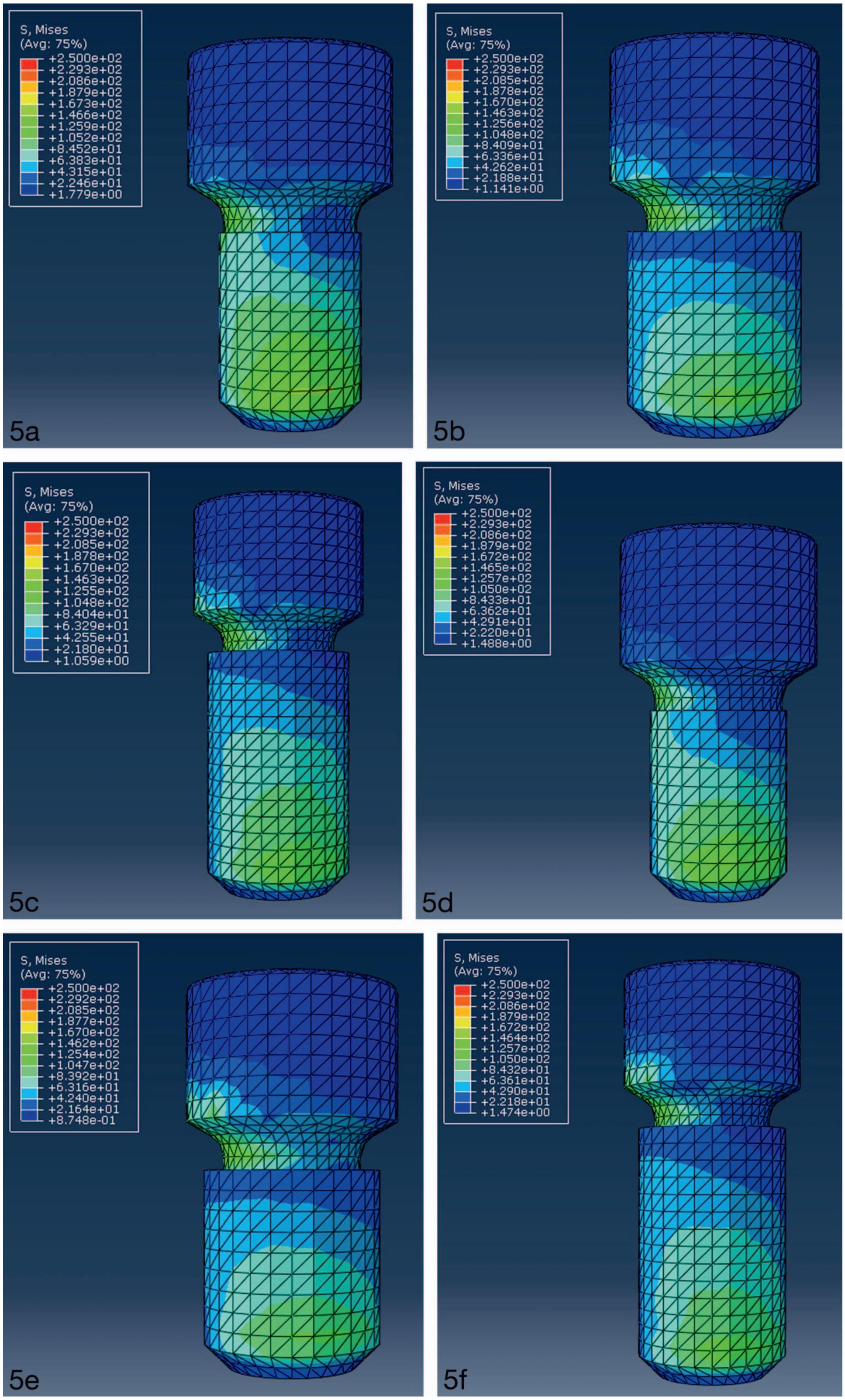

FIGURE 5. Stress distribution in the anterior prosthetic screw on the loaded side. (a) Short and narrow screw, short abutment group. (b) Short and wide screw, short abutment group. (c) Long and wide screw, short abutment group. (d) Short and narrow screw, long abutment group. (e) Short and wide screw, long abutment group. (f) Long and wide screw, long abutment group.

was 17.6% lower in the SWS group than in the SNS group and 12.7% lower in the SWL group than in the SNL group. Depending on the height of abutment, the peak stress in the posterior screws was 3.8% lower in the SNL group than in the SNS group and 3.0% lower in the LWL group than in the LWS group, whereas it was 1.9% higher in the SWL group than in the SWS group.

Discussion

The aim of this study was to evaluate the stress patterns induced in prosthetic screws with different screw lengths/diameters and abutment heights, using finite element analysis. As the length and diameter of the screw increase, the stress on the posterior prosthetic screw tends to decrease because the contact area of the screw increases.[40] As the screw diameter increases, the preload increases, and the clamping force increases at the screw joint, which may reduce screw loosening.[41] In this study, it was found that the longer and wider the screw was, the greater the contact area with the abutment, and the lesser the stress concentrated on the screw. This may suggest that the short and narrow screw was likely to loosen more frequently than the long and wide screw. The rate of decrease of the stress value in the posterior prosthetic screw was greater with an increase in diameter of the screw than with an increase in length. This may suggest that the diameter of the screw is more related to stress concentration than the length of the screw.

These results are similar to the results of previous studies on other components in single-implant restorations.[42,43] Kanneganti et al[42] reported that, as the length of the abutment screw increased, the stress decreased. In addition, Himmlova et al[43] reported that an increase in the implant length and diameter led to a decrease in the maximum von Mises equivalent stress values on the implant, and an increase in the implant diameter decreased the maximum von Mises equivalent stress values more than an increase in the implant length.[43]

In contrast, as the height of the abutment increases, the rate of decrease in the stress value in the posterior prosthetic screw was relatively low. This may suggest that the height of the abutment is less related to the stress concentration than the length or diameter of the screw. This is because, as the abutment height increases, the contact area between the metal framework and the abutment increases, and stress redistribution may occur. Nevertheless, there are some reports that increasing the abutment height has the benefit of decreasing marginal bone loss.[44–48] Therefore, it can be considered clinically.

In this study, all stress values of the posterior prosthetic screws were higher than those of the anterior prosthetic screws. These findings indicate that posterior screw loosening may occur more frequently than anterior screw loosening. Stress on the posterior prosthetic screw tended to be concentrated on the lower part of the screw, as previously reported,[32] whereas stress on the anterior prosthetic screw tended to be distributed on the neck and lower part of the screw.

Loosening of a screw from the joint occurs when the separating force acting on the screw joint is greater than the clamping force holding them together.[49] The preload is created when the screw is first tightened, and it remains on the screw until the end of the assembly process.[50] The preload is affected by the finishing of the interface, the friction between the components, the geometry, and the material properties. The higher the preload, the greater the force required to loosen the components.[51]

The screw-loosening process occurs as follows: when an external force such as occlusal loading is applied on the screw joint, it causes thread slippage and releases the preload of the screw. If there is a continuous reduction of the preload, causing it to fall below the critical level, the thread will spin and lose the function at the screw joint, thus releasing the screw.[50] Screw loosening is also related to cycling fatigue, oral fluids, varied chewing patterns, and loads.[51] An occlusal overload can cause fatigue or loosening of the screw.[52]

In this study, the stress values were lower than the tensile and compressive strengths of titanium, which prevented the occurrence of immediate fracture.[35] However, finite element analysis has limitations because it simulates a living tissue that is not constant in its natural state and cannot precisely be replicated in the oral cavity.[2,53] Longitudinal clinical follow-up and clinical trials are needed to confirm the results of this study.

Conclusions

Within the limitations of this study, it may be suggested that an increase in the length and diameter of the prosthetic screw decreases the stress on the screw. This may in turn reduce the incidence of complications such as screw loosening or fracture.

Abbreviations

LWL: long and wide screw, long abutment
LWS: long and wide screw, short abutment
SNL: short and narrow screw, long abutment
SNS: short and narrow screw, short abutment
SWL: short and wide screw, long abutment
SWS: short and wide screw, short abutment

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Note

The authors declare no conflict of interest.

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