Numerical Analysis of a Dental Implant System Preloaded with a Washer

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Gold screw loosening is a problem that frequently affects dental implants. The application of a preload has been the main means of preventing loosening. However, this measure has not been able to eliminate its occurrence. In this study the effect of a washer in a Brånemark-type implant on the loosening conditions of the retaining screw was investigated using a finite element simulation. The simulation indicated that a washer may significantly increase the tolerance of a screw against loosening. This is accomplished by increasing the tolerance of the implant against deformation. The addition of a customized washer to a dental implant system may offer a very simple and inexpensive solution for the persistent problem of screw loosening.
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Loosening and fracturing of abutment and retaining screws appear to be significant problems in the application of dental implants.[1,2] Fracture may occur if a screw is fatigued or overloaded, a condition likely exacerbated by loosening. Loosening, which takes place if a screw slips and detaches from its abutments, is generally attributed to the complexity of masticatory loading conditions, but may also occur because of rotational misfit.[3] To counter this loosening, screws are torqued up to a prescribed value, putting an implant system under an axial preload. It has been found that the application of higher preloads generally decreases the frequency of loosening. There is a limit, however, to the amount of preload that can be applied because of yield and fracture concerns.

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Unfortunately, preloading has not been able to completely eliminate the occurrence of screw loosening. Masticatory loading, fatigue, and yield have all been mentioned as probable contributing mechanisms of loosening. Each of these mechanisms could potentially reduce the effect of a preload; however, none has been identified with certainty. Apart from bruxing, the maximum expected biting forces on a single-tooth implant condition seem to induce stress levels lower than those generated by clamping forces.[4,5] Although asymmetric loads may lead to local stress distributions that could locally exceed the clamping forces,[4,6] particularly on implants without snug fittings, it is not obvious that they would be sufficient to loosen a whole screw. Fatigue, as a crack propagation process under subcritical cyclic loading, would decrease the elastic clamping energy of the prestressed screw or abutment, leading to loosening. However, without any detailed information about fatigue failure in implants, the role of fatigue is an elusive factor that is often used too easily to explain poorly understood phenomena. Preload is achieved by stretching a screw elastically. Obviously, no additional preload is achieved if an implant system is stressed beyond its elastic limit. It has been shown in various studies that the manufacturer's recommended torque for tightening an implant will result in prestresses well below the yield point.[4,7] The reported need for retightening of implant screws could also point to stress relaxation as a fourth possible mechanism of screw loosening that may defeat all current pretensioning efforts. However, more experimental data is needed to confirm the existence of stress relaxation in dental implant materials. Vibration and damping behavior are other factors that are known to affect screw loosening in many engineering applications. Although there have been no reports that the dynamic behavior of the maxillofacial area is a critical factor for implants, it should be considered as a fifth possible screw-loosening mechanism.

Whatever the exact mechanisms, the clamping forces of preloads are a result of the strain energy stored in the implant system when the screws are torqued. Loosening requires lengthening of the screw and/or shortening of the abutments. In engineering, washers are widely used to prevent screw loosening. Adding a washer increases the stored strain energy. The aim of this study was to demonstrate the effect of a washer used in conjunction with a gold retaining screw in a Brånemark-type implant system. It was hypothesized that a washer could effectively increase the tolerance of the gold screw abutment structure to deformation.

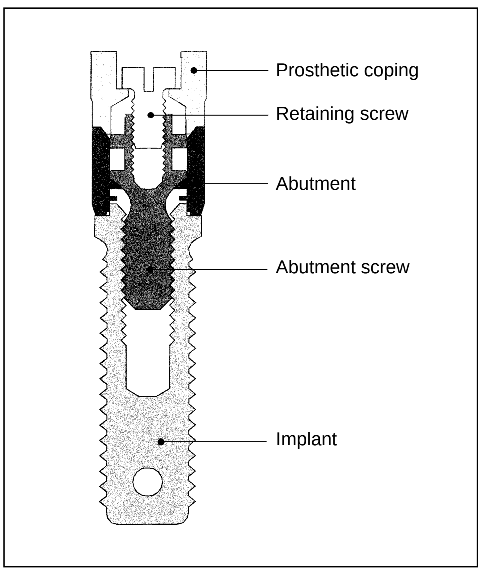

Fig 1 Cross section of a Brånemark-type implant system.

Materials and Methods

A finite element simulation was used to demonstrate the mechanism of a washer in an implant system. This method has been used previously to investigate contact stresses between dental implant components.[5,6] In a finite element analysis, a whole structure is subdivided into a number of small simple-shaped elements, for which individual deformation (strain and stress) can be more easily calculated than for the whole undivided structure. Once the deformation of all the small elements is calculated simultaneously, the total deformation of the whole structure can be reconstructed. The finite element analysis consisted of the following 5 steps: *(1)* the creation of geometrical models (element meshes); *(2)* the assignment of material properties; *(3)* the application of preloads; *(4)* the calculation of contact stresses and deformations; and *(5)* the processing of the results.

A cross section of a standard Brånemark single-implant system (regular body) was digitized using NIH Image Software. The system consisted of a gold retaining screw, a gold prosthetic coping, a titanium abutment, a titanium abutment screw, and a titanium implant (Fig 1). An axisymmetrical mesh was created in I-DEAS (Master Series SDRC, Milford, OH) and MENTAT (MARC Analysis Research, Palo Alto, CA), using triangular and quadrilateral axisymmetrical elements (Fig 2). Although real screw threads are not axisymmetric, the simplified axisymmetrical representation was sufficient to simulate, in an axial direction, the principle of adding a washer to an implant system.

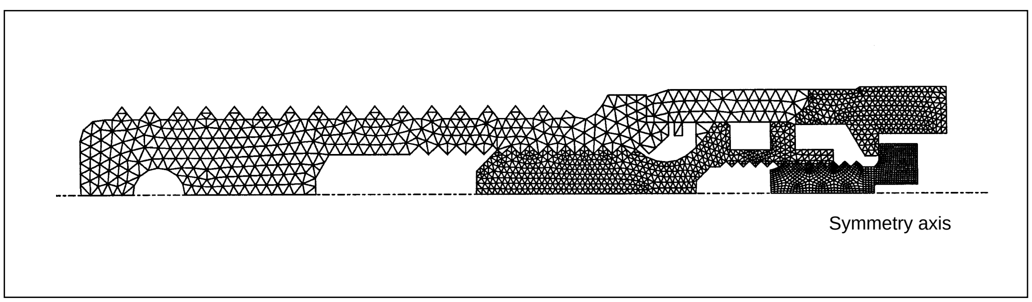

Fig 2 Axisymmetric finite element mesh.

Two variations were modeled: *(1)* the original implant without a washer and *(2)* an implant system with a washer placed between the gold retaining screw and the gold prosthetic coping.

Washers can have many shapes and can be made from various materials. For the purpose of this demonstration, the washer was arbitrarily given aluminum properties and a saucerlike shape (its total thickness was chosen to equal the distance between 2 simulated threads of the retaining screw) (Fig 3). The applied mesh density (number of elements and number of nodes) and mechanical properties[6,8] for each modeled implant component are listed in Table 1.

The outer thread of the titanium implant (at the bone-implant interface) was considered fixed. Contact analysis assured the union and transfer of loads and deformation between the different components, featuring a coefficient of friction of 0.3. The retaining screw was preloaded up to a maximum value of 350 N, using uniaxial thermal contraction in the unthreaded screw shaft only. The uniaxial thermal contraction effectively shortened the screw in the area between the threads and the head, creating clamping loads in the screw without decreasing the original unstressed screw diameter. The preload was then decreased in 10 increments until the screw was loose, ie, the thread of retaining screw lost contact with the abutment screw (zero clamping loads).

Results

The axial load in the gold screw was determined versus axial displacement of the screw head (measured at the contact area). The results are expressed in Fig 4, which shows the axial deformation (in μm) required in the upper implant assembly (retaining screw, abutment screw, cylinder) to become loose as a function of axial preload. Clinically, axial preload (or clamping force) is applied by torque. Within the elastic domain, higher torque values will result in higher preload values. The figure shows nearly linear relationships between the axial displacements and clamping loads. The implant system with the washer required up to 15 times more axial deformation than a conventional system without washer before it became loose.

Since the addition of a washer to the implant system does not affect the preload value, the stress distribution for both systems (with and without washer) is almost identical (Fig 5). Only at the washer-implant contact areas did the stress distribution (not the magnitude) differ slightly between the 2 configurations. Note that the washer is not

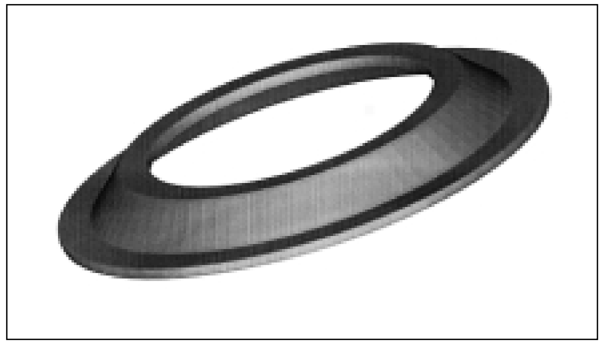

Fig 3 Saucer-shaped washer.

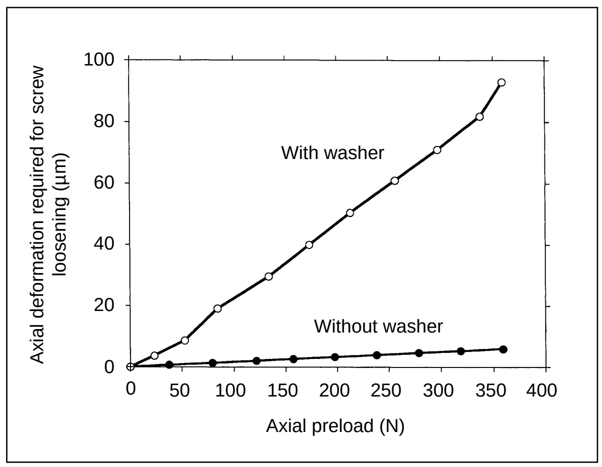

Fig 4 Graph indicating the axial deformation that is required to make the gold retaining screw lose contact with its abutments as a function of the axial preload.

Table 1 Applied Mechanical Properties and Mesh Density Parameters

Component	Elastic modulus (GPa)	Poisson's ratio	Elements/nodes
Gold retaining screw	100[6]	0.3[6]	860/954
Gold prosthetic coping	100[6]	0.3[6]	496/289
Titanium abutment	117[6]	0.3[6]	88/66
Titanium abutment screw	117[6]	0.3[6]	924/556
Titanium implant	117[6]	0.3[6]	603/389
Aluminum washer	77[8]	0.33[8]	87/120

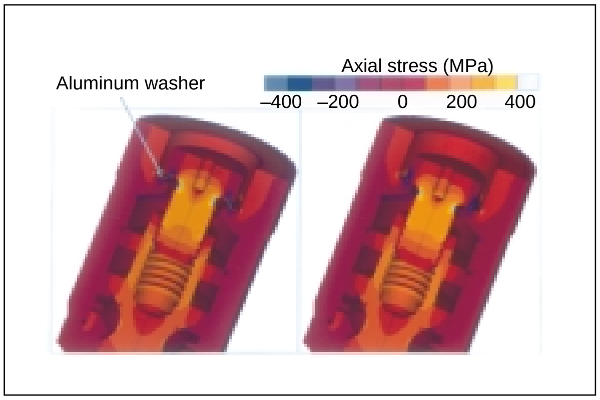

Fig 5 Distribution of axial stresses in an axisymmetric implant system with and without a washer.

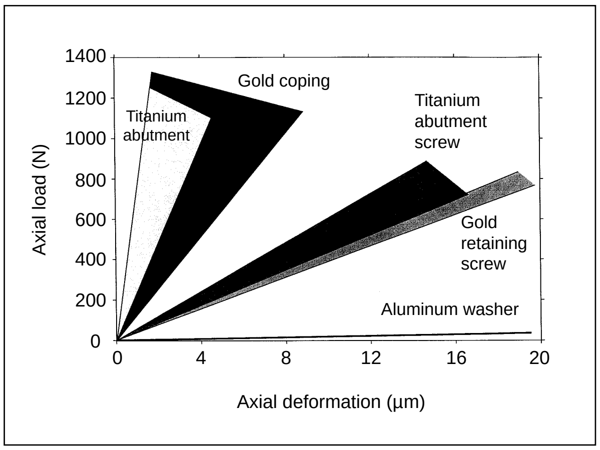

Fig 6 Graph showing axial stiffness domains for various implant components.

fully compressed, since compression beyond that point would effectively eliminate any further advantage of the washer system.

The stiffness (elongation versus load) for each implant component was determined and is shown in Fig 6. Since stiffness is a structural parameter rather than a material property, its value depends on the component's geometry and the location of determination, hence the domain representation of Fig 6. The figure illustrates the relatively high stiffness behavior of the implant components compared with the washer.

Discussion

Although both the abutment and retaining screws may loosen, only loosening of the retaining gold screw was considered in this study. A retaining screw secures the attachment of a prosthetic coping onto the abutment. Since occlusal forces load the retaining screw indirectly via its abutments, it is a change in the shape of these abutments (eg, deformation of the coping or loosening of the abutment) and/or elongation through stress relaxation that will cause the retaining screw to become loose.

The relationship between change in shape, ie, deformation, under influence of loads acting on the implant can be expressed in the stiffness factor (loading-elongation ratio). Fig 6 shows the axial stiffness of individual components of the implant assembly. If a system has a high overall stiffness, high loads will result in small deformations. Applied to the implant assembly, this means that a small deformation could also rapidly eliminate the preload in a relatively stiff retaining screw. Note that deformation is caused not only by external mechanical loads but can also be induced by stress relaxation or enhanced by crack propagation.

In this study, a washer was considered as a possible means of preventing screw loosening and was added to the implant system. A washer is an elastic, axially deformable ring with a relatively low stiffness (Fig 6). The washer was placed between the coping and the retaining screw. The numerical simulation indicated that the implant system with the washer required a much larger deformation of the retaining screw abutments or elongation of the retaining screw itself for an equal drop in preload value compared to the original implant configuration without a washer (Fig 4). The washer, therefore, dramatically increased the elastic energy without increasing the preload value (Fig 5). Without the washer, small deformations caused a comparatively steep drop in clamping forces (Fig 4). Note that the addition of a washer increases the effective shank length between engaged threads and screw head by the thickness of the compressed washer. However, the relative effect of a slightly longer effective shank was only minor, as can be expected from the large difference in their component stiffnesses shown in Fig 6 (note that the indicated stiffness ranges contain various effective shank length values). The shorter engaged thread length of the retaining screw with the washer, on the other hand, may indicate the need for longer screws.

It should be noted that the principle shown here is also applicable to other configurations. As mentioned before, washers may come in many shapes and materials. Washer stiffness is determined by a combination of shape and material elastic modulus. The range of applicable washer materials is determined by their biocompatibility and durability in the oral environment. Different washer configurations will alter the absolute value of the stored strain energy of the implant assembly, as will other factors, such as surface roughness, that have not been considered in the current model. Experimental measurements need to be carried out to determine the realistically possible improvement with a washer against loosening. However, the principle of using a washer as demonstrated in this simulation remains the same. Finally, note that only the retaining screw was secured with a washer in this simulation. Obviously, the abutment screw can also be fitted with this device, which would have a similar effect on its loosening behavior, as was demonstrated for the retaining screw.

Conclusion

The use of a washer in a Brånemark-type removable implant system is a simple and inexpensive solution that may prevent loosening and fracture of the retaining screw. The application of a washer does not affect the applied preload and may defeat or delay the already suspected mechanisms of screw loosening—masticatory loading, fatigue, and yield—as well as vibration (by changing the dynamic response) and stress relaxation processes.

Acknowledgments

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