Console Abutment Loading in Craniofacial Osseointegration

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Retention of implant-supported facial prostheses presents challenges in design that may lead to use of freestanding abutments. This is particularly so in the midface and orbit. Individual implant success rates are lower in these regions, and bone remodeling capacity may be compromised by combined modality cancer therapy. The present study was undertaken to determine the variations in load delivery so as to compare the use of long cantilevers and offset abutments with freestanding axially loaded abutments. The study revealed not only that the loads delivered are not trivial, but also that the highest loads generated are frequently delivered at the cervix of the implant. The long cantilevers produced the highest laterally acting cervical loads, whereas the 30-degree and 60-degree Console abutments delivered the highest laterally acting cervical loads of all the Console abutments. The potential of long cantilevers and offset abutments to deliver significant loads should be considered when designing retention for a facial prosthesis.
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Key words: console abutments, craniofacial osseointegrated implants, facial prostheses, finite element analysis, loading, lone-standing abutments

Creating a path of insertion for implant-supported facial prostheses can be challenging. This is particularly so in orbital and midfacial prostheses because of unavoidable compromises of implant position and angulation. To accommodate these challenges, the Console abutment (Nobel Biocare AB, Göteborg, Sweden) was developed (Fig 1). The Console abutment provides for offset placement of the retentive component away from the body of the abutment.[1] The offset extension of the abutment allows for selection of 30-, 60-, 90-, and 110-degree angles away from the long axis of the abutment body. The offset extension carries a threaded seat that allows connection of a variety of retentive components. Frequently, Console abutments are employed in freestanding situations.

Loading of an implant creates a strain distribution in the surrounding bone.[2–5] It is believed that this strain is a sensor signal for the remodeling mechanism of bone.[6,7] Axial loading of an implant is considered desirable, whereas creation of a bending moment results in elevated strain distribution in the surrounding bone.[1,4] In the case of osseointegrated implants, the relationship between strain levels and the remodeling response of bone is not precisely understood.[2] A commonly held position is that reducing strain in the bone surrounding the implant is beneficial. Frost's Mechanostat theory proposes that in long bones, strain below approximately 200 $\mu\epsilon$ results in bone loss, whereas equilibrium by remodeling is maintained between 200 $\mu\epsilon$ and 2500 $\mu\epsilon$ in compression of 1500 $\mu\epsilon$ in tension.[7] The relevance of this data to craniofacial osseointegration has not been established; however, it is believed that for certain midfacial situations, the strain levels for remodeling equilibrium would be considerably lower considering that the bone was essentially nonloadbearing prior to placement of the implant.

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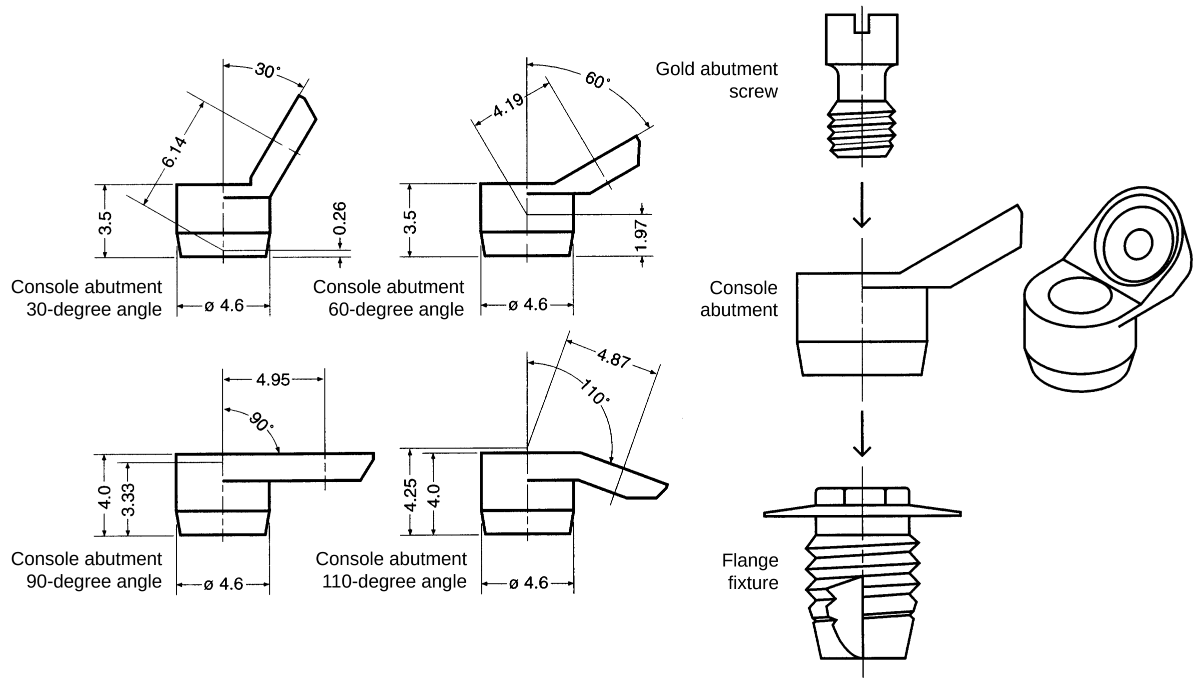


Fig 1 Console abutments. The offset extension of the abutment allows for selection of 30-degree, 60-degree, 90-degree, or 110-degree angles away from the long axis of the abutment body (dimensions in millimeters).

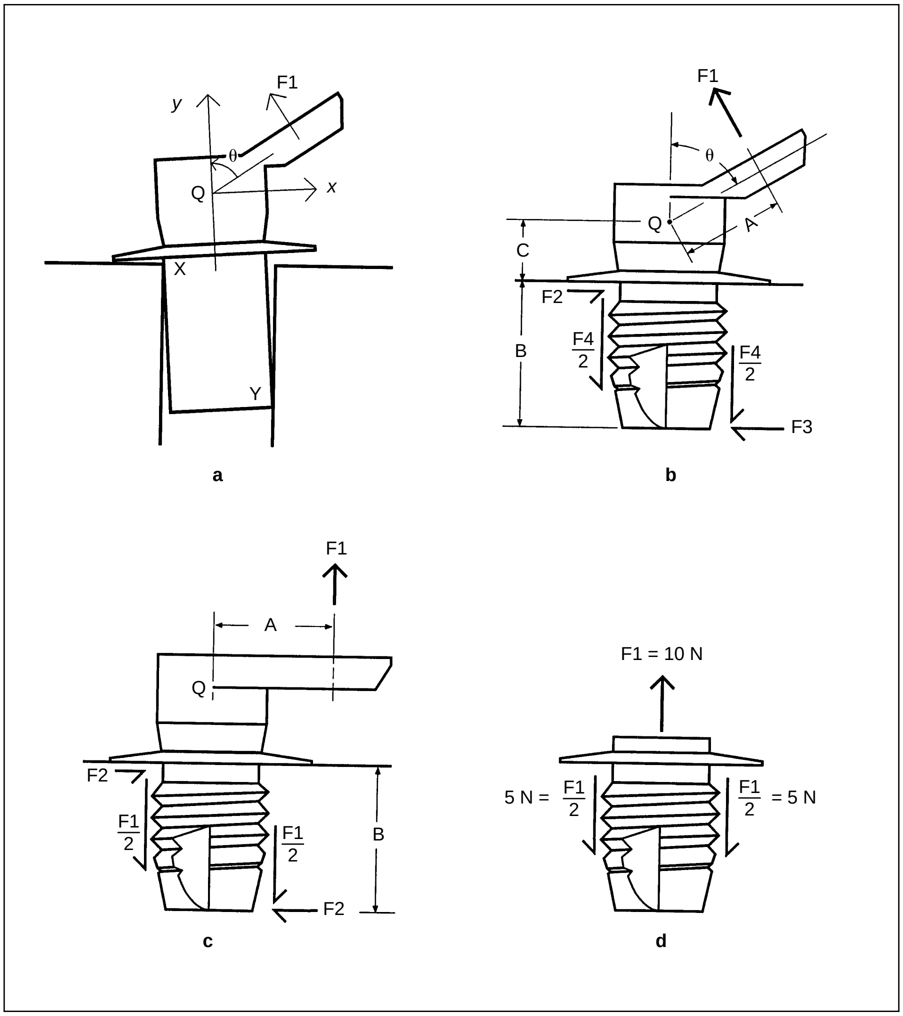
The loads delivered by retention mechanisms used in craniofacial osseointegration have been described. The approximate load delivered by individual retentive components is 6 to 11 N.[8] For retentive systems that apply axial loads to the implant, this is the only load the hard tissue must carry. Cantilevering the retentive components modifies the loading pattern and increases the strain in the bone surrounding craniofacial osseointegrated implants. As a result, it has been suggested that use of long cantilevers should be judicious or avoided altogether.[1,4,9] Depending on the angle selected, Console abutments offer shapes that introduce a nonaxial load through the action of a cantilever with a varied length. To provide guidelines for these various situations, it is of interest to compare the loads and strains induced in the bone by the Console abutments with those induced by cantilevers of varying length. One objective of the present study was to estimate the loads delivered to the surrounding bone both by conventional freestanding cantilevers and by Console abutments. A second objective was to compare the strain distributions associated with conventional freestanding cantilevers and Console abutments with those arising from purely axial loads. The aim of this study was to develop a means of comparing the loads and strains induced in the bone by various abutment designs.

Materials and Methods

The dimensions of Console abutments and implants were obtained from Nobel Biocare AB (Fig 1). To compare the loads delivered to the bone by Console abutments and by cantilevers of varying lengths, a typical load of 10 N (caused by removal of the retention mechanism) was theoretically applied at the attachment point of the cantilever or abutment. Calculations were made to determine the loads delivered to the bone surrounding the craniofacial osseointegrated implant (diameter 3.75 mm; nominal length 3 mm and 4 mm) for several lengths of cantilever and the four angulations of the Console abutment. The detailed strain distribution produced in each of the cantilever and Console abutments was evaluated by means of a finite element analysis (FEA) in a manner similar to that done previously.[4]

Calculation of Load Delivery. To appreciate the loading patterns created in hard tissue by craniofacial osseointegrated implants, a simplified method was devised for comparing the forces developed in

Figs 2a to 2d Models of load delivery to abutments: (a) enlarged view of implant-bone interaction; (b) force system for Console abutment; (c) force system for cantilever abutment; (d) force system for axially loaded abutment. F1 = 10 N load delivered by retentive component; F2 = load delivered laterally to implant cervix; F3 = load delivered laterally to implant apex; F4 = load delivered axially to implant; u = angle of the offset extension to the long axis of the implant-abutment assembly; A = dimension between long axis of abutment and screw hole in offset extension; B = length of implant; C = height of cantilever origin.



any particular case of eccentrically applied loads to those when the loading is purely axial. This approach enlarges on an idea suggested by Rangert.[1] If the loads are eccentrically applied, as shown in Fig 2a, and if the implant is assumed to be slightly smaller than the hole in the hard tissue into which it is to fit, then the resisting forces are applied at positions X and Y only. (This is, of course, a somewhat crude approximation, but it serves to concentrate the forces in the regions in which they would be expected to be greatest in the actual case.) The free-body diagram of the implant and abutment shown in Fig 2b includes the two horizontal (lateral) forces F2 and F3 (at the cervical and apical ends, respectively), along with the vertical force, which has been divided evenly between the two positions. This last assumption is made so that the resisting forces F2, F3, and F4 can be statistically determined. A somewhat more detailed analysis, in which this assumption is relaxed, shows a relatively insignificant difference in the maximum loads calculated (see Appendix 1).

Using the equations of static equilibrium for the system by taking the sum of the forces in the x and y directions, as well as the sum of the moments about point Q, allows determination of the three unknowns (F2, F3, and F4) from the expressions

$$F2 = (F1/B)[A + (B+C)\cos\theta]$$
$$F3 = (F1/B)[A + C\cos\theta]$$
$$F4 = (F1)\sin\theta$$

From these general expressions, special cases can easily be determined. For the case in which θ = 90 degrees, the three forces reduce to

$$F2 = F3 = F1(A/B)$$
$$F4 = F1$$

which is the cantilever case shown in Fig 2c. The larger the eccentricity (A) of the cantilever, the greater the magnitude of the lateral loads F2 and F3. The calculation of load for the cantilevers was made

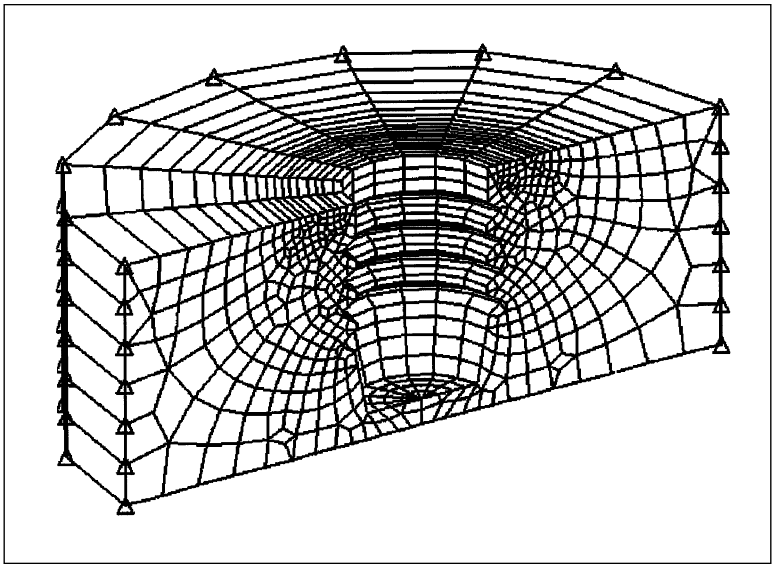


Fig 3 Finite element mesh for strain analysis.

for both 3-mm and 4-mm length implants and for cantilever lengths of 5 mm and 10 mm. The retentive load (F1) applied was 10 N in each case. If the eccentricity of the cantilever goes to 0, the result is the base case of the axially loaded implant. In the formulation above, the lateral forces F2 and F3 vanish, and the axial load F1 of 10 N is simply resisted by F4 (see Fig 2d), with 5 N applied on each side.

For the general case of Console abutments, the retentive load is no longer applied perpendicular to the surface of the hard tissue. Because the applied retentive load has a component parallel to the surface of the hard tissue, the forces F2 and F3 are not equal. The calculation of the load delivery was made for the 30-degree, 60-degree, 90-degree, and 110-degree abutments, again with a retentive load of 10 N.

Once the forces F2, F3, and F4 are calculated (for either the cantilever or the abutments), the maximum force (Fmax) can be determined by vectorially adding the forces on each side (ie, F2 and F4/2, F3 and F4/2). This results in Fmax being

$$\mathrm{Fmax} = [(\mathrm{F2})^2 + (\mathrm{F4}/2)^2]^{1/2} \quad \text{OR} \\ = [(\mathrm{F3})^2 + (\mathrm{F4}/2)^2]^{1/2}$$

whichever is larger. (For the cantilever, F2 and F3 are equal and F4 is the same as F1.) As stated above, in this simple analysis, the axial load (F4) was arbitrarily divided equally on both sides of the implant.

Strain Distribution Resulting From the Console Abutments. While the elementary analysis above, which developed the equivalent forces acting in the bone, allows a comparison between different geometric configurations, the detail of the strain distributions can be modeled using the FEA method as previously described.[4] The bone type modeled was for solid compact bone, and the implant types evaluated were for both 3-mm and 4-mm Brånemark craniofacial flanged implants (SEC 001 and SEC 002, Nobel Biocare AB). A Young's modulus of 103.4 GPa was assumed, and the flange was arbitrarily given a reduced modulus of 25.0 GPa to represent that the flange has a series of holes in it. The 10 N load (F1) was placed at the center of the screw hole and perpendicular to the offset extension of the abutment. Figure 3 shows the detail of the finite element mesh used and indicates the fixed boundary conditions of the radial, hoop, and vertical directions along the outside circumferential edge while the base margin was free. The interface condition assumed the implant and bone element were joined (osseointegrated). The analysis was performed using the commercial software package Algor (Pittsburgh, PA). This software provided a function for meshing enclosed objects with a two-dimensional mesh that could be comprised of triangles or quadrilaterals or a combination of the two. The density of the mesh could be globally or locally refined using built-in functions. The three-dimensional models that used brick elements were formed from the two-dimensional meshes by rotating and copying them around the vertical axis every 22.5 degrees. Because of the plane of symmetry in this type of loading, only half of the model was used in the finite element solution.

The output of the FEA provides the nine components of each of the stress and strain tensors at each node of the elements. In addition, the software provides the greatest and least principal values of these stress and strain components. These principal values are normal stresses or strains, and these can be either

Table 1 Loads and Strains Induced in Bone by a 10 N Tensile Load Applied to Craniofacial Osseointegrated Implants

Abutment implant design	Dimensions A (mm)	B (mm)	C (mm)	Forces F2 (N)	F3 (N)	F4 (N)	Fmax (N)	Maximum principal tensile strain (με)	Force ratio to standard	Strain ratio to standard
Standard 4.0-mm implant	0.00	4.20	Any	0.0	0.0	10.0	5.0	23.0	1.0	1.0
Standard 3.0-mm implant	0.00	3.20	Any	0.0	0.0	10.0	5.0	28.7	1.0	1.2
Console/4-mm implant:										
30 degrees	6.14	4.20	0.26	23.8	15.2	5.0	23.9	124.8	4.8	5.4
60 degrees	4.19	4.20	1.97	17.3	12.3	8.7	17.8	103.6	3.6	4.5
90 degrees	4.95	4.20	3.33	11.8	11.8	10.0	12.8	84.8	2.6	3.7
110 degrees	4.87	4.20	4.25	4.7	8.1	9.4	9.4	76.4	1.9	3.3
Console/3-mm implant:										
30 degrees	6.14	3.20	0.26	28.5	19.9	5.0	28.6	127.9	5.7	5.6
60 degrees	4.19	3.20	1.97	21.2	16.2	8.7	21.6	106.1	4.3	4.6
90 degrees	4.95	3.20	3.33	15.5	15.5	10.0	16.3	87.8	3.3	3.8
110 degrees	4.87	3.20	4.25	7.3	10.6	9.4	11.6	78.4	2.3	3.4
Cantilever/4-mm implant	5.00	4.20	Any	11.9	11.9	10.0	12.9	85.2	2.6	3.7
	10.00	4.20	Any	23.8	23.8	10.0	24.3	150.1	4.9	6.5
Cantilever/3-mm implant	5.00	3.20	Any	15.6	15.6	10.0	16.4	90.0	3.3	3.9
	10.00	3.20	Any	31.3	31.3	10.0	31.6	155.4	6.3	6.8

positive (tensile stresses or strains), negative (compressive stresses and strains), or one positive and the other negative. They represent the largest and smallest values in any direction at the point under consideration. (Note that the largest [if positive] would correspond to the greatest tensile stress or strain, while the smallest [if negative] would correspond to the greatest compressive stress or strain.) In this study, as strain is assumed to be the sensor for remodeling in the bone, it is used to compare the various situations. For the loading considered, the maximum absolute value of these principal strains was tensile, and, as a result, the strain distributors shown below are only for the principal values of the tensile strains. The distributions for the compressive principal strains were similar, but the absolute magnitudes of the distributions were generally lower than were those for the tensile strains.

To compare the specific loading and bone configuration for the various implant designs, it is desirable to have single numbers that can be used as a measure of the level of the strains induced by the loaded implant. For this purpose, the average value of the principal strains (both tensile and compressive) of all the nodes for each element was determined. This provided average principal strains for each element. Rather than simply report the largest of these average values found in the mesh, all of the cortical bone elements were sorted on the basis of their average principal strains. A further average value was then taken for the 5% (by volume) of the cortical bone elements that contained the largest individual element averages. This averaging eliminates the variations that could occur as a result of using one mesh over any other, and it is believed to be a measure of the level of strain in the most highly strained region of the cortical bone. This quantity provided a means of comparison of the various situations discussed, using single numbers for the largest tensile and compressive principal strains rather than comparing complete strain distributions. In what follows, these averages are referred to as the maximum principal strains. For the loading considered, these maximum values are tensile.

Results

A summary of all of the calculations, both for the loads and for the strains induced in the bone by the retentive load of 10 N, are given in Table 1. Included are the pertinent dimensions of the particular designs used. The results for the standard abutment are reproduced from a previous study and are used for comparison.[4] It should be noted that in the case of the standard abutment or the cantilevers, because the load F1 is applied parallel to the axis of the implant, the forces and strains developed in the bone are independent of the size of the abutment, and therefore dimension C does not enter into the calculations.

The results indicate, as suggested above, that the cantilevers or Console abutments immediately introduce lateral forces (F2 and F3) that must be carried by the bone. For many of the designs, these lateral forces are much greater than the axial forces. For example, the 30-degree Console abutment (connected to a 4-mm implant) has a lateral load of approximately 24 N, while the axial load on each side is only 2.5 N (F4/2). This increase in force related to the lateral components is mirrored in the increase in maximum principal strain that the finite element analysis shows. For the same case, the maximum strain increases from 23 to 125 $\mu\epsilon$, while the maximum load increases from 5 N to 24 N.

The detailed results for the Console abutments show that as the angle of the abutment increases, the forces and strains decrease. This means that the 30-degree case produces the highest levels of force and strain while the 110-degree case produces the least. Comparing the levels of force and strain with the axially loaded standard abutment design suggests that the 30-degree Console abutment causes maximum forces and strains in the order of 5 times higher for the 4-mm implant and 5.6 times higher for the 3-mm implant. As the angle of the Console abutment increases, the ratio of force and strain to the standard case falls to the range of 2 to 3 times (110-degree case).

The results for the conventional cantilever system show that for a 5-mm-long arm, the level of force and strain are approximately 3 times those in the standard case for a 4-mm implant and 3.5 times those in the standard case for a 3-mm implant. When the length of the cantilever is increased to 10 mm, these comparisons rise to the 5 to 6 range for the 4-mm implant and to the 6 to 7 range for the 3-mm case. It is interesting to note that the ratios of force and strain for the 10-mm-long cantilever are only slightly higher than the ratio for the 30-degree Console abutment for the same length of implant.

Overall, the ratios of forces and maximum principal strains allow a simple means of comparing the loading, which the particular design will produce when a typical retentive load is placed on a freestanding craniofacial implant. The basis of comparison is a freestanding axially loaded standard abutment connected to a craniofacial implant. The relatively straightforward calculation of an equivalent force system is somewhat simplified, but nonetheless provides results that are close to the more detailed ones from the finite element analysis. Figures 4 to 11 each compare the maximum principal strain distributions for the 3-mm and 4-mm implants with the various Console abutments. In these diagrams, the implant has been removed; however, the retentive load (not shown) would be applied in the plane shown and on the right side of the diagram. These distributions show the concentration of higher strains that occur near the cervix of the implant, as well as the fact that the 3-mm cases have slightly larger regions with higher strains. Note that for the 110-degree case, the region of highest strain is now on the left rather than on the right side of the implant. The analysis points to these regions as the ones most likely to be mechanically overloaded and therefore at the most risk.

All of the above results were for the case of a craniofacial implant placed in solid cortical bone with the bone-implant interface fully integrated. Because this is not always the situation, it should be understood in situations where the cortical bone is thinner, the loads and strains calculated will be considerably higher. For example, in the case of a cortical bone thickness of 1.5 mm, the difference between the 3-mm and the 4-mm implant is irrelevant, and the lateral loads (F2) produced by a 10-mm arm cantilever are 66.7 N and the Fmax is 66.8 N. The load ratio with the original standard abutment on a 4-mm implant in solid cortical bone is 13.4 and the maximum principal strain ratio is 14.3. This situation results in magnification of the bone loading of somewhere between 13 and 14 times the original case.

Discussion

Craniofacial osseointegrated implants have been associated with a higher individual implant failure rate when compared to dental implants.[9,10] The variable implant failure rate is dependent on the anatomic site of placement and on a variety of other factors that have been shown to be related to loss rates in the craniofacial region. Craniofacial osseointegrated implants are frequently placed in bone compromised by combined modality cancer therapy. Given that the fundamental cause of implant loss is not understood, a conservative approach to loading these implants has been advocated.[1,4]

The loads and maximum principal strains calculated for long cantilevers and Console abutments do not appear to be trivial. In the present study, the loads delivered by 10-mm-long cantilevers ranged up to 30 N, which is similar to the case of the 30-degree Console abutments. The geometry of the long cantilevers and some of the angled abutments caused the loads and strains to be increased up to 6 times that when a standard abutment on an implant was loaded axially. Since this result was obtained for the ideal situation, where the implant was fully integrated in cortical bone, when the cortical bone is thinner or has been compromised, the loading from a single retention point can be potentially destructive. An important anticipated difference in load delivery between craniofacial and dental implants would be the frequency with which the loads are delivered. The loads would be delivered far more frequently in the case of dental implants, since the loads calculated for craniofacial implants are only anticipated with facial prosthesis connection and removal. The associated strain rate history developed by the connection and removal of the facial prosthesis might be significant in relation to the remodeling capacity of the surrounding bone. Currently, there is no clinically convenient method for directly assessing the potential of bone to remodel. Since the relationship between mechanical

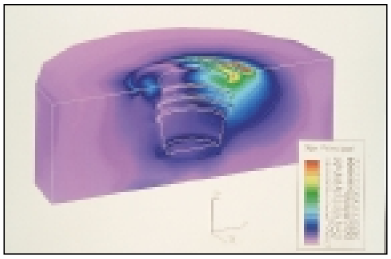


Fig 4 Maximum tensile strain distribution of 30-degree Console abutment connected to 3.0-mm-length Brånemark craniofacial osseointegrated implant.

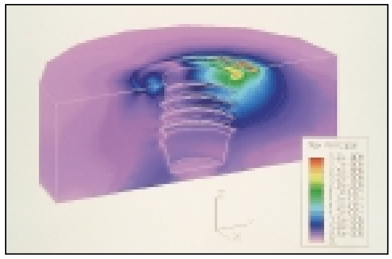


Fig 5 Maximum tensile strain distribution of 30-degree Console abutment connected to 4.0-mm-length Brånemark craniofacial osseointegrated implant.

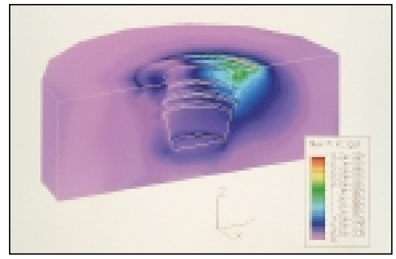


Fig 6 Maximum tensile strain distribution of 60-degree Console abutment connected to 3.0-mm-length Brånemark craniofacial osseointegrated implant.

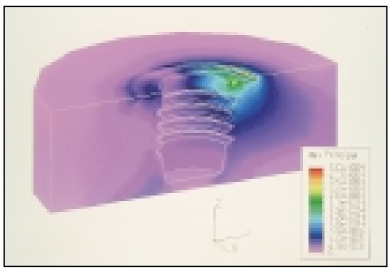


Fig 7 Maximum tensile strain distribution of 60-degree Console abutment connected to 4.0-mm-length Brånemark craniofacial osseointegrated implant.

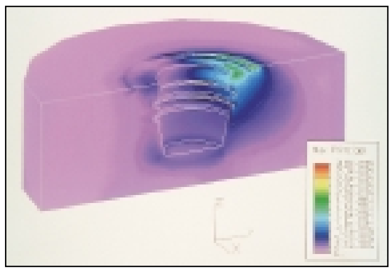


Fig 8 Maximum tensile strain distribution of 90-degree Console abutment connected to 3.0-mm-length Brånemark craniofacial osseointegrated implant.

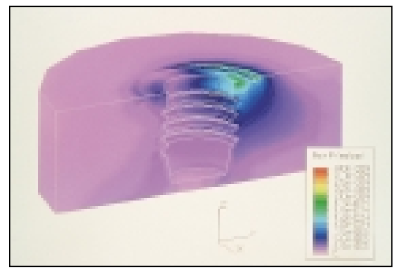


Fig 9 Maximum tensile strain distribution of 90-degree Console abutment connected to 4.0-mm-length Brånemark craniofacial osseointegrated implant.

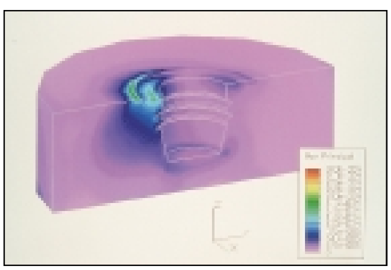


Fig 10 Maximum tensile strain distribution of 110-degree Console abutment connected to 3.0-mm-length Brånemark craniofacial osseointegrated implant. Note that the maximum tensile strain occurs on the side opposite to the other angulations of Console abutment.

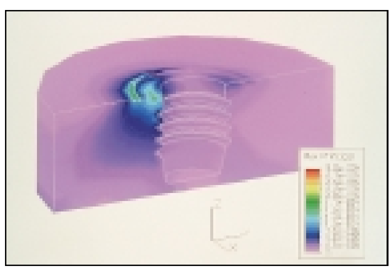
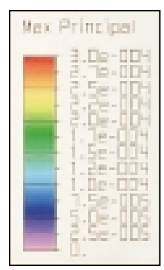


Fig 11 Maximum tensile strain distribution of 110-degree Console abutment connected to 4.0-mm-length Brånemark craniofacial osseointegrated implant. Note that the maximum tensile strain occurs on the side opposite to the other angulations of Console abutment.



Key for Figs 4 to 11

stimuli and remodeling response of bone is not established,[2] drawing correlations between load and outcome of treatment is not yet possible.

In the case of the 30-degree and 60-degree Console abutments for both 3-mm and 4-mm implants, the highest calculated loads were delivered horizontally at the cervix of the implant. Likewise, the conventional 10-mm cantilevers also delivered lateral loads of similar magnitude to the cervix of the implant. Lateral loads to the neck of the implant are considered undesirable, as they are thought to be a cause of cervical bone loss. The 90-degree Console abutments have equally opposing forces acting laterally at the cervix and apex of the implant, which is more mechanically desirable. The 110-degree Console abutments had the lowest maximum loads and relatively low lateral load delivery.

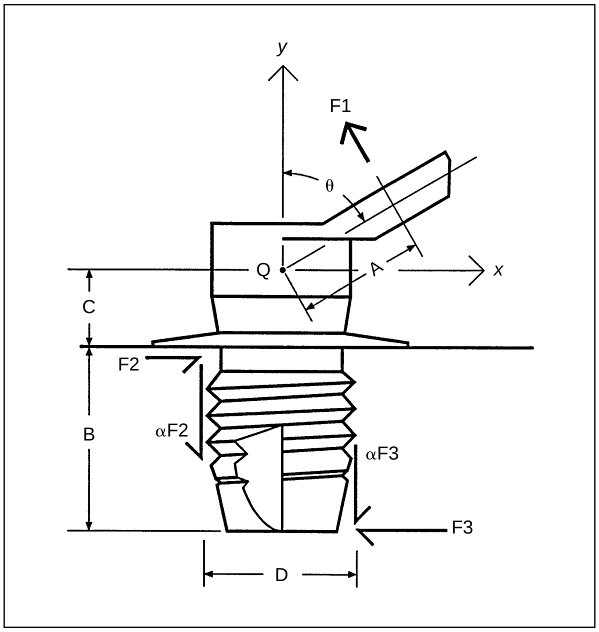


Fig 12 Alternate diagram of load delivery by Console abutment.

Summary

Creating retention elements for implant-supported facial prostheses may require the use of cantilevers or abutments that have offset designs. In some situations, these designs may result in freestanding abutments. The calculated load delivery to the bone indicated that the loads generated should not be considered trivial. While current understanding of craniofacial bone remodeling in relation to craniofacial osseointegrated implants is inadequate to make specific retention-design rules, it is suggested that an intuitive approach to risk assessment be adopted. Loads delivered to craniofacial osseointegrated implants by long cantilevers and offset abutments have the potential to deliver significant loads and should be employed judiciously.

Appendix 1

Forces applied to the hard tissue were analyzed on the basis of a number of assumptions. It is possible to calculate the forces from a statistically determinate case, but to alter the assumptions on which the calculations are based. One of the alternatives is shown in the free-body diagram of Fig 12, in which the components of the forces in the axial direction are assumed to be proportional to the corresponding lateral ones (either F2 or F3). (This is similar to the assumption used for the case of static friction, when the frictional force is assumed to be proportional to the normal force.) To make the problem statistically determinate, the proportionality constant is assumed to be the same. Summing the forces in the x and y directions yields

$$F2 = (F1/2)(\sin\theta/\propto + \cos\theta)$$
$$F3 = (F1/2)(\sin\theta/\propto - \cos\theta)$$

where the proportionality constant $\propto$ is given by the solution of the quadratic equation (obtained from summing moments about point Q)

$$\propto^2 D\cos\theta + [2A + (2C+B)\cos\theta]\propto - B\sin\theta = 0$$

and the lowest positive root is chosen. The dimension D is taken as the outer thread diameter of 3.75 mm. As an example for the 30-degree Console abutments (4-mm implant), the Fmax calculated using the more complex calculation is 25.1 N, while the value for the calculation in Table 1 is 24.6 N. This difference of 2% is not considered significant given the very approximate nature of the calculations. The simpler approach shown in the main text is sufficient to give an appreciation of the differences in loading created by the various designs. For the extended cantilevers in particular, both analyses give the same result, since F2 and F3 are equal in magnitude.

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