Comparison of Load Distribution for Implant Overdenture Attachments

Joseph A. Porter, Jr, BS, MS[1]/Vicki C. Petropoulos, DMD, MS[2]/John B. Brunski, MS, PhD[3]

Purpose: *The aim of this study was to compare the force and moment distributions that develop on different implant overdenture attachments when vertical compressive forces are applied to an implant-retained overdenture.* ***Materials and Methods:*** *The following attachments were examined: Nobel Biocare bar and clip (NBC), Nobel Biocare standard ball (NSB), Nobel Biocare 2.25-mm-diameter ball (NB2), Zest Anchor Advanced Generation (ZAAG), Sterngold ERA white (SEW), Sterngold ERA orange (SEO), Compliant Keeper System with titanium shims (CK-Ti), Compliant Keeper System with black nitrile 2SR90 sleeve rings (CK-70), and Compliant Keeper System with clear silicone 2SR90 sleeve rings (CK-90). The attachments were tested using custom strain-gauged abutments and 2 Brånemark System implants placed in a test model. Each attachment type had one part embedded in a denture-like housing and the other part (the abutment) screwed into the implants. Compressive static loads of 100 N were applied (1) bilaterally, over the distal midline (DM); (2) unilaterally, over the right implant (RI); (3) unilaterally, over the left implant (LI); and (4) between implants in the mid-anterior region (MA). Both the force and bending moment on each implant were recorded for each loading location and attachment type. Results were analyzed using 2-way analysis of variance and the Duncan multiple-range test.* ***Results:*** *Both loading location and attachment type were statistically significant factors ($P < .05$). In general, the force and moment on an implant were greater when the load was applied directly over the implant or at MA.* ***Discussion:*** *While not significant at every loading location, the largest implant forces tended to occur with ZAAG attachments; the smallest were found with the SEW, the SEO, the NSB, the CK-70, and the CK-90. Typically, higher moments existed for NBC and ZAAG, while lower moments existed for SEW, SEO, NSB, CK-90, and CK-70.* ***Conclusion:*** *For different loading locations, significant differences were found among the different overdenture attachment systems.*
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Key words: *dental precision attachments, forces and moments, loading, overdenture, strain gauge*

Mechanical attachments fixed in tooth roots to enhance the retention and stability of an overdenture have been used for nearly a century. Attachment fixation for overdentures originated in Switzerland around 1898 and was popularized 60 years ago by Gilmore.[1] Endosseous implants are being used in the same manner as were tooth roots more than 100 years ago and have been shown to be reliable abutments for both retention and support of overdentures.[2] The components of the implant-retained overdenture are[3]: *(1)* the implant; *(2)* the abutment, which contains one of the mating male or female attachment components depending on the system used; and *(3)* the overdenture, which houses the counterpart attachment component.

When complete dentures are converted into implant-retained overdentures using attachments, one observed advantage is that masticatory function is improved.[4] Many different attachments available today may be used to support an implant-retained overdenture. A previous in vitro investigation studied and quantified the amount of retention for implant-retained overdentures to aid the clinician in

[1]Former Graduate Student and Research Assistant, Department of Biomedical Engineering, Rensselaer Polytechnic Institute, Troy, New York.
[2]Assistant Professor, Department of Restorative Dentistry, University of Pennsylvania School of Dental Medicine, Philadelphia, Pennsylvania.
[3]Professor, Department of Biomedical Engineering, Rensselaer Polytechnic Institute, Troy, New York.

Reprint requests: Dr Vicki C. Petropoulos, 4001 Spruce Street, University of Pennsylvania School of Dental Medicine, Department of Restorative Dentistry, Philadelphia, PA 19104-6003. E-mail: VPetropoulos@aol.com

attachment selection based on the amount of retention desired rather than anecdotal findings.[5] However, retention should not be the only factor to consider when designing an implant-retained overdenture. As the patient functions with an implant-retained overdenture, loads are transmitted to alveolar bone surrounding the implants, as well as to the abutments and residual ridges. It is important not to cause unfavorable loads on the implant abutments that house the attachments, as these loads can be detrimental to the osseointegrated implants. Previous studies have studied force transmission with various overdenture attachments.[6] Other studies developed theoretical models for predicting implant loading.[7] Finite element computer models have also been used to predict the loading of implants with different designs. While such models have been useful in predicting trends in loading with fixed prostheses in partially and completely edentulous patients, it is not clear exactly how such models apply to implant-retained overdentures.

Few experimental studies have examined the specific load transfer characteristics of various overdentures under either in vivo or in vitro conditions. Duyck and associates used strain gauges to measure the axial forces and bending moments on implants retaining the overdentures of 5 patients using ball and socket attachments and bar-and clip attachments with and without bilateral extensions.[8] While that study reported that ball and socket systems bore somewhat higher axial loads, and, conversely, that bar and clip systems induced somewhat higher implant bending moments, the differences were not statistically significant.[8] Menicucci and coworkers also used strain gauges to measure the axial forces on implants retaining the overdentures of 3 patients using ball and socket and bar and clip attachments.[9] Additionally, the load taken by the mucosa was directly measured by mounting a load cell to the underside of the overdenture. While it was concluded that ball and socket attachments distributed more load to the supporting gingiva—and conversely less load to the retaining implants—than bar and clip attachments, statistical significance was not mentioned.[9]

Another study done by Menicucci and associates using a 3-dimensional (3-D) finite element model revealed complicated distributions of stresses on the mandible; however, the stress distribution with the ball and socket attachment systems was more favorable overall.[10] Finally, Federick and Caputo examined overdentures retained by bar and clip attachments, extracoronal resilient attachments (ERA) (Sterngold, Attleboro, MA), and a combination of a bar and clip with distal ERA attachments in a photoelastic model. It was concluded that ERA attachments alone tended to provide the most equitable transfer of load to the bone surrounding the implants.[11]

While analytic and 3-D finite element models have been useful in helping to understand load transfer from prosthesis to implants, it remains to be seen how well these models can predict in vivo results. In the meantime, laboratory experiments with a physical model of an implant-retained overdenture can be useful in assessing load transfer from prosthesis to implants because such a model is practical and reasonably realistic. In any case, the resultant loading of the implant abutment constitutes essential design information. The designer must know the resultant loading to understand the mechanical environment of both the implant and interfacial tissues. Without this information, the designer must resort to guesswork and trial and error.[12] With so few experimental results available on the biomechanics of different overdenture attachments, the goal of this study was to use strain-gauged abutments to measure and compare the forces and moments acting on implant abutments when static compressive forces simulating biting forces were applied to various common designs of implant-retained overdentures.

MATERIALS AND METHODS

Attachment Systems

The attachment systems examined are as follows (Figs 1a to 1f).

1. Nobel Biocare bar and clip (NBC) (Nobel Biocare USA, Yorba Linda, CA): 2 standard abutments, 2 gold screws, 1 round gold bar, 1 CM clip spacer, and 1 CM clip (Cendres and Metaux SA, Biel-Bienne, Switzerland)
2. Nobel Biocare standard ball (NSB): 2 ball abutments, 2 plastic caps with rubber O-rings, and 2 spacers
3. Nobel Biocare 2.25-mm-diameter ball (NB2): 2 ball abutments, 2 metal caps with spring, and 2 spacers
4. Zest Anchor Advanced Generation (ZAAG) (Zest Anchors, Escondido, CA): 2 Zest implant abutments and 2 Zest males with spacers
5. Sterngold ERA white (SEW) (Sterngold): 2 zero-degree abutments, 2 black processing males, and 2 white males
6. Sterngold ERA orange (SEO): 2 zero-degree abutments, 2 black processing males, and 2 orange males

7. Compliant Keeper System with titanium shims (CK-Ti) (Merrill Mensor, Papamoa, Tauranga, New Zealand): 1 round gold bar, 2 gold screws, 1 CM clip, 2 lower abutments, 2 upper abutments, and 2 titanium shims
8. Compliant Keeper System with black nitrile 2SR90 sleeve rings (CK-70): 1 round gold bar, 2 gold screws, 1 CM clip, 2 lower abutments, 2 upper abutments, and 2 black nitrile 2SR90 sleeve rings
9. Compliant Keeper System with clear silicone 2SR90 sleeve rings (CK-90): 1 round gold bar, 2 gold screws, 1 CM clip, 2 lower abutments, 2 upper abutments, and 2 clear silicone 2SR90 sleeve rings

An overdenture was specially designed for each attachment system. Each overdenture/attachment system was subjected to vertical forces acting at 4 different locations on the prosthesis. Tests were repeated 5 times, giving a total of 20 measurements for each attachment system. Because their respective manufacturers prefabricate these attachments, they are standardized in shape, size, and fit, which should limit variability within the system.

Fig 1 Attachment systems examined. (a) Nobel Biocare round gold bar with counterpart CM clip attachment. (b) Compliant Keeper System with abutments, black nitrile sleeve rings 2SR90 and gold bar with counterpart CM clip attachment (clear silicone sleeve rings 2SR90 and titanium shims not shown). (c) Nobel Biocare standard ball abutment with counter part O-ring cap attachment. (d) Nobel Biocare 2.25-mm ball abutment with counterpart titanium cap attachment. (e) Sterngold abutment with counterpart orange attachment (white attachment not shown). (f) Zest Anchor Advanced Generation abutment with counterpart attachment.

Test Model

An acrylic resin mandibular test model was used to simulate the clinical situation. While this study was an in vitro study only, an attempt was made to simulate the gingival soft tissue covering the mandible by using Gingival Masque (Coltene/Whaledent, Brooklyn, NY), a resilient silicone material that was placed on all edentulous areas. While the resiliency of the soft tissue and human mandible varies from person to person depending on the amount of available bone and soft tissue, this mandibular test model remained constant throughout the experiment, thereby controlling this variable. The silicone material had a nominal elastic modulus on the order of 2 MPa,[13] which is the same order of magnitude as the approximate elastic moduli reported in uniaxial tensile tests of soft tissues such as skin, eg, 1 MPa.[14] Two Brånemark System implants (Nobel Biocare), 3.75 mm in diameter and 10 mm in length, were placed in the symphyseal regions. While every attempt was made to place the implants parallel to one another, some degree of divergence was likely to exist, although the implants were not more than 5 degrees away from being parallel. Two implants have been found to be adequate for an implant-retained overdenture model,[15] so this was the model on which all the tests were performed.

A cast chrome-cobalt framework was fabricated to act as a denture base in the edentulous regions. Overdentures can be fabricated with either acrylic resin or metal bases.[16] The advantage of using a metal framework instead of an all-acrylic resin base was that the framework remained constant for all tests; this enabled the use of the same test model and overdenture base for all attachment systems (Fig 2).

The different overdenture attachment systems were interchanged on the framework. Four 3-mm-diameter stainless steel nuts were soldered to the framework: 2 in the most anterior region of the outer limits of the framework, and 2 in the most posterior region of the implants. These steel nuts allowed the interchange of overdenture housings that contained the different overdenture attachment systems. This metal framework remained attached to the overdenture housings throughout the experiments.

Overdenture Housing

The overdenture housing was constructed similar to the previous design of Petropoulos and coworkers.[5] This housing (Fig 3) consisted of a removable acrylic resin component that occupied the most anterior region where the cast chrome-cobalt

Fig 2 The resilient acrylic test model with 2 Brånemark implants placed in the symphyseal regions. Also shown is the cast chrome-cobalt framework with the denture base and 2 standard Brånemark abutments.

Fig 3 Resilient acrylic test model with cast chrome-cobalt framework and an example of an overdenture housing with sample clip attachment (bar not shown).

framework encircled the 2 implants. Its purpose was to activate the implant attachments being studied, while the counterpart attachments remained screwed into the test model implants. A prototype housing was fabricated from VLC blue Triad material (Dentsply, York, PA). The prototype housing was placed in a denture-duplicating flask (Implant Innovations, West Palm Beach, FL) that contained condensation silicone putty (Zetalabor, Zhermack, Rovigo, Italy). The flask was opened after the material had set for 20 minutes, and the prototype was removed. An impression was made of the prototype housing. Clear orthodontic resin and liquid monomer (Caulk, Milford, DE) were mixed according to manufacturer recommendations and placed inside the flask. The flask was then submerged in warm water in a pressure cooker under air pressure (15 psi for 35 minutes).

Fabrication of Sample Attachments

All free-standing stud-type attachment systems (NSB, NB2, SEW, SEO) were activated by screwing the keyway or key component of the abutments (depending on which system was used) into the implants and by positioning its counterpart attachment on top with its spacer. VLC Triad reline material (Dentsply) was used to activate the attachment components. Each sample overdenture attachment system had one part embedded in the overdenture housing and the other part screwed into the test model implants (Fig 3).

For the Nobel Biocare bar and clip system and the Compliant Keeper System, a 30-mm round gold bar was cut to 17 mm to fit between the 2 abutments of the test model. GC resin (Fuji, Tokyo, Japan) was used to attach the bar to the gold cylinders of each system. The bar was invested and soldered. The metal clip was activated for retention by pushing the 2 parallel sleeves together with light finger pressure. The Nobel Biocare clip was activated using its spacer in the overdenture housings with the VLC Triad reline material. For the Compliant Keeper System, the titanium shims were used on the abutments when activating the clip. The titanium shims were used as a non-mobile control for the resilient sleeve rings (nitrile and silicone sleeve rings; 2SR90) in the Compliant Keeper System and the other mobile test elements. For confirmation of positive seating of the overdenture housings onto the framework, the holes of the housings were used as reference points; they were checked for alignment with the nuts of the framework for all the sample attachments.

Strain-Gauged Abutments

Customized and calibrated strain-gauged abutment transducers were used to measure the forces and moments that developed on the abutment portion of the implants. The methodology of bonding the strain gauges and calibrating the abutments to perform as strain-gauged transducers was similar to that of Glantz and associates[17] and is described in more detail in the Appendix.

Loading Setup

Compressive static loads were applied 5 times at each of 4 different locations on the prosthesis: *(1)* bilaterally over the distal midline (DM); *(2)* unilaterally over the right implant (RI); *(3)* unilaterally over the left implant (LI); and *(4)* between implants in the mid-anterior region (MA). Loads were applied axially (vertically) using a custom-made loading device and with a magnitude of 100 N, which simulates a moderate level of biting force on an implant-retained overdenture[18] (Fig 4). The resulting strains on the implants were measured by the abutment transducers and recorded by a computer-based data acquisition system. From the recorded strain readings, the corresponding forces and moments on the implants were calculated according to a calibration method based on the work of Tuttle[19] (see Appendix).

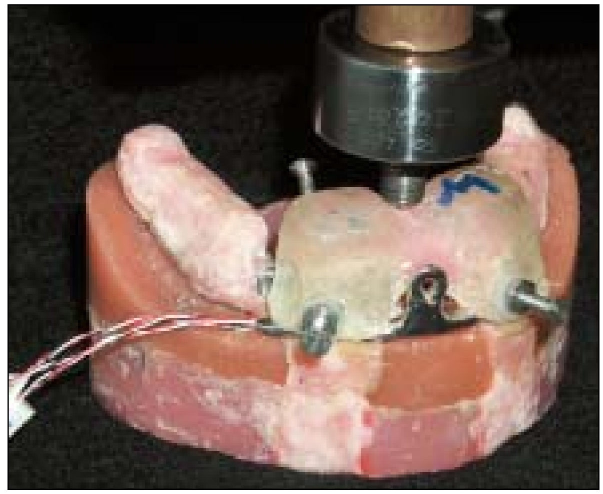

Fig 4 Loading setup. Weight is applied to the overdenture with a custom loading device with an attached load cell, while abutment transducers measure the corresponding forces and moments on the implants.

Statistics

The measured forces and moments were analyzed statistically using a 2-way analysis of variance (ANOVA) examining both the attachment type and the applied load location. Multiple comparisons were made using the Duncan multiple range test for each implant/load location.[20]

RESULTS

Based on a 2-way ANOVA, both factors—attachment type and applied load location—were significant at the .05 confidence level. The Duncan multiple range test for each implant/load location showed significant differences at the .05 level among the individual overdenture attachment systems. The results for loading over the RI, LI, and MA locations are presented in Figs 5 to 10.

The magnitudes of implant forces and moments when loaded over the DM were, as expected, small in comparison to the other sites. In general, however, the 2 ERA attachments (SEW and SEO), the Nobel Biocare Standard Ball (NSB) attachments, and the CK-70 and CK-90 sleeve rings demonstrated lower implant forces and moments than the remaining attachment types.

Implant Forces When Overdenture Was Loaded over the Right Implant

The right implant bore the majority of the applied load (Fig 5). Among the various attachment systems, multiple comparisons indicated that nearly all of the systems were significantly different at the .05 confidence level for this loading location. In general, however, the attachment systems were classified into 4 groups:

1. The SEW attachments transmitted approximately 20% of the applied load to the supporting implants.
2. The SEO and NSB attachment systems transmitted approximately 50% of the applied load to the implants.
3. The NB2, NBC, CK-70, and CK-90 attachment systems transmitted about 75% of the applied load to the implants.
4. The ZAAG and CK-Ti attachment systems transmitted approximately 100% of the applied load to the implants.

Implant Forces When Overdenture Was Loaded over the Left Implant

In this case, the left implant took the majority of the applied load (Fig 6). While the forces taken by the left implant varied significantly among most of the tested attachment systems, few significant differences were found among attachment systems with respect to the resultant forces on the right implants. This could be explained primarily by the smaller magnitude of forces on the right implants. In terms of the total force taken by both implants, again the attachment systems fell into 4 general groups:

1. The SEW attachments allowed less than 20% of the applied load to be carried by the supporting implants.

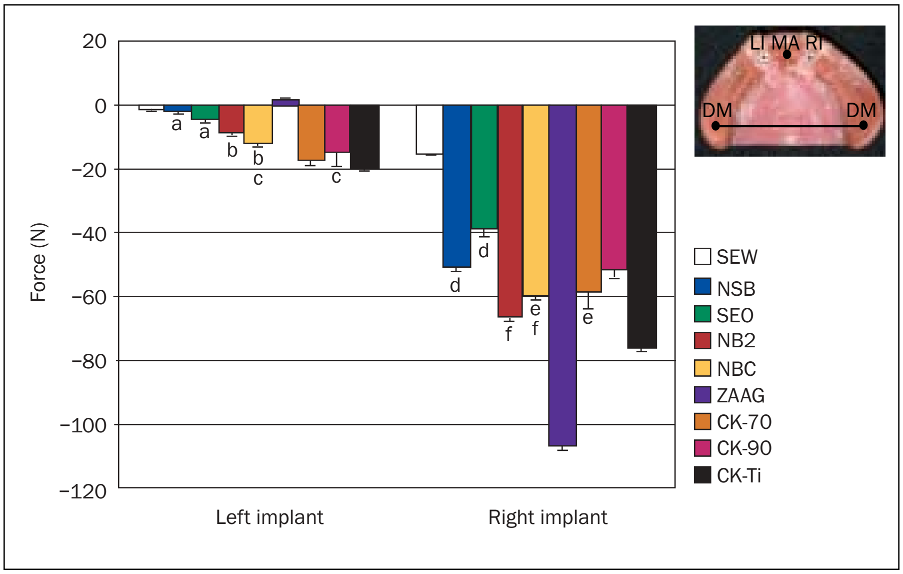

Fig 5 Measured implant forces with −100 N force applied over the right implants (RI). Columns with corresponding letters indicate attachment systems that are not statistically different.

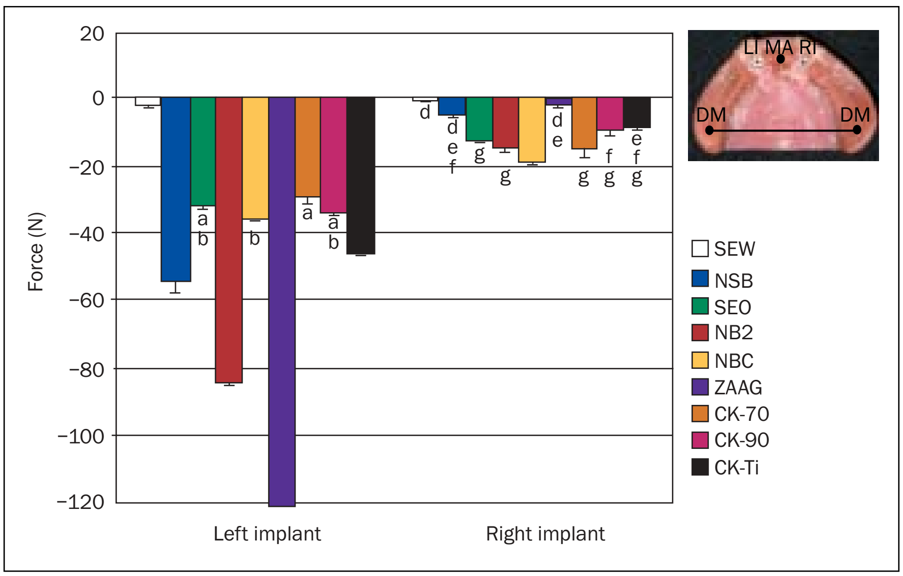

Fig 6 Measured implant forces with −100 N force applied over the left implant (LI). Columns with corresponding letters indicate attachment systems that are not statistically different.

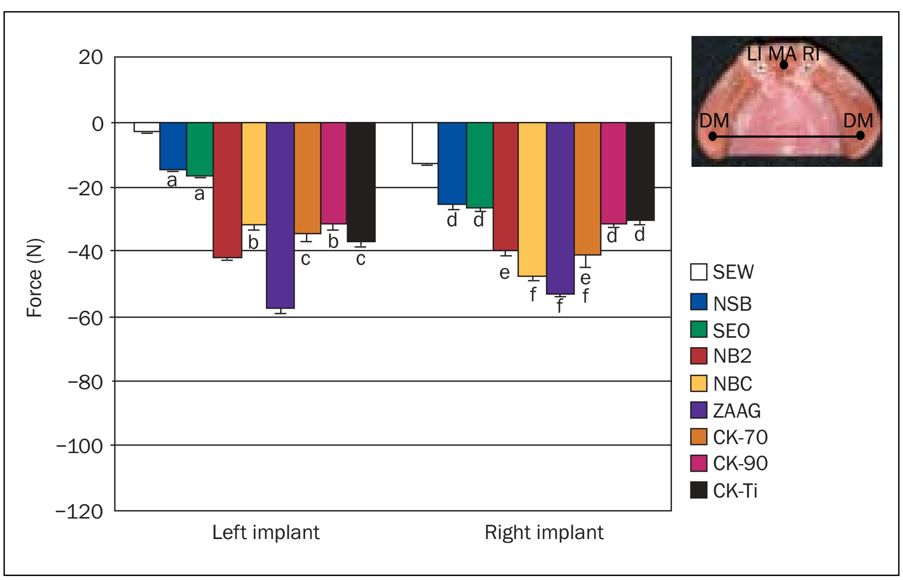

Fig 7 Measured implant forces with −100 N force applied between implants in the mid-anterior region (MA). Columns with corresponding letters indicate attachment systems that are not statistically different.

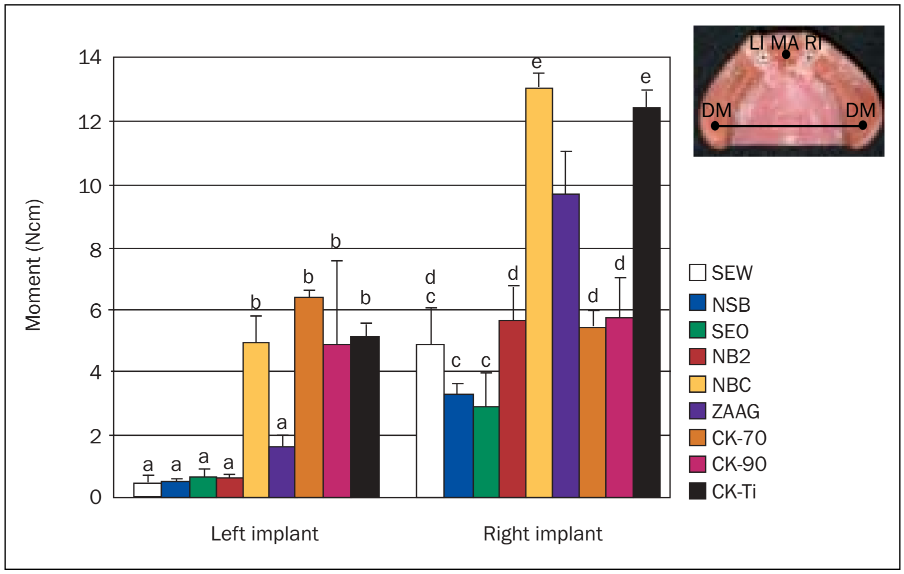

Fig 8 Measured implant moments with −100 N force applied over the right implant (RI). Columns with corresponding letters indicate attachment systems that are not statistically different.

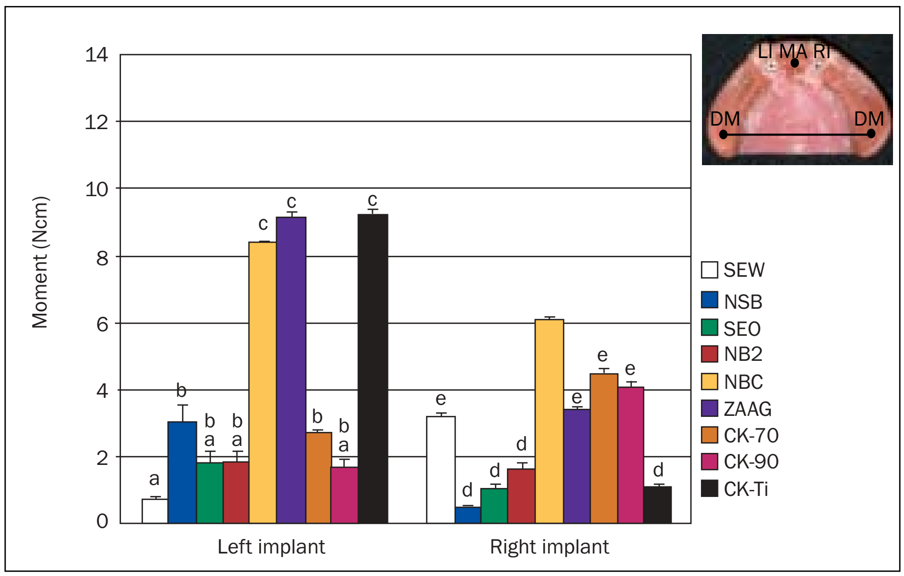

Fig 9 Measured implant moments with −100 N force applied over the left implant (LI). Columns with corresponding letters indicate attachment systems that are not statistically different.

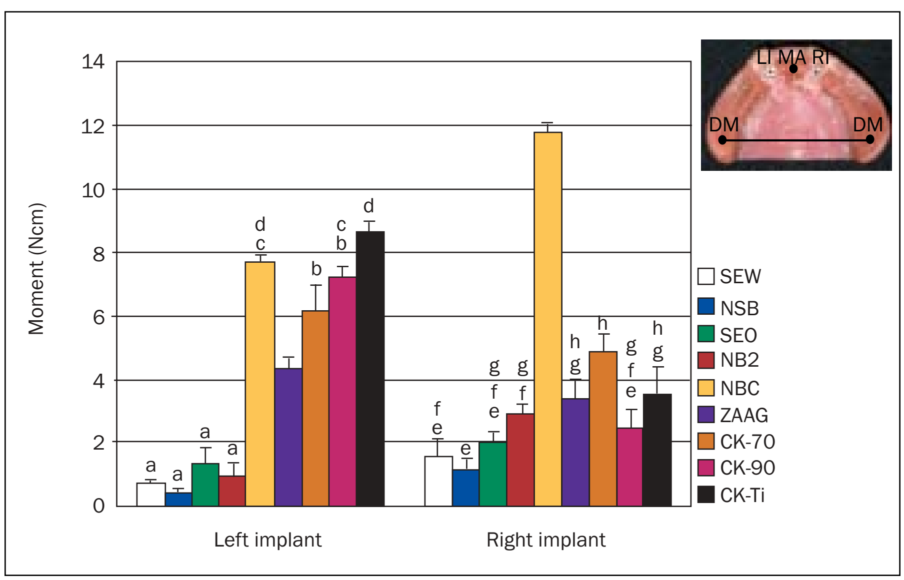

Fig 10 Measured implant moments with −100 N force applied between implants in the mid-anterior region (MA). Columns with corresponding letters indicate attachment systems that are not statistically different.

2. The SEO, NBC, CK-70, CK-90, and CK-Ti attachment systems transmitted approximately 50% of the applied load to the implants.
3. The NSB attachment system transmitted about 75% of the applied load to the implants.
4. The NB2 and ZAAG attachment systems transmitted approximately 100% of the applied load to the implants.

Implant Forces When the Overdenture Was Loaded in the Mid-anterior Region

With the load applied to the overdenture between the 2 supporting implants, the implants received approximately the same level of force (Fig 7). Significant differences ($P < .05$) among implant forces with the various attachment systems again allowed the systems to be divided into 4 separate groups:

1. The SEW attachments allowed less than 20% of the applied load to be carried by the supporting implants.
2. The SEO and NSB attachment systems transmitted approximately 50% of the applied load to the implants.
3. The NB2, NBC, CK-70, CK-90, and CK-Ti attachment systems transmitted about 75% of the applied load to the implants.
4. The ZAAG attachments transmitted approximately 100% of the applied load to the implants.

Implant Moments When the Overdenture Was Loaded over the Right Implant

For this type of loading, the right implant generally experienced higher moments than the left implant (Fig 8). Among the various attachment systems, multiple comparisons indicated that most pairwise combinations were significantly different at the .05 confidence level. In general, however, the trend was that NSB, NB2, SEW, SEO, and CK-70 permitted lower moments to develop than NBC, CK-90, CK-Ti, and ZAAG attachment systems, which tended to be more rigid.

Implant Moments When the Overdenture Was Loaded over the Left Implant

As with the case of loading over the right implant, moments were frequently found to be higher on the left implant (Fig 9). Among the various attachment systems, multiple comparisons indicated that pairwise comparisons with systems having low implant moments were not significantly different at the .05 confidence level. However, most of the systems producing higher moments were significantly different. Generally, the trend observed when the overdenture was loaded over the right implant still held for loading over the left implant; that is, for the free-standing stud-type attachments (NSB, NB2, SEW, SEO, CK-90, and CK-70), there were lower moments than with the NBC, CK-Ti, and ZAAG attachment systems.

Implant Moments When the Overdenture Was Loaded in the Mid-anterior Region

As with implant forces, the implant moments were approximately symmetric; ie, for each attachment system, the left and right implant experienced nearly the same moment. Significant differences between pairs of attachment systems are summarized in Fig 10; free-standing stud-type attachments (NSB, NB2, SEW, SEO) permitted lower moments than bar-type attachments (NBC, CK-70, CK-90, CK-Ti), with the exception of the ZAAG attachments. Significant differences were observed for the NBC bar attachment (for moments measured on the left implant) and CK-Ti (for moments measured on the right implant); these systems demonstrated the highest moments as compared to all the other attachments.

DISCUSSION

This investigation studied how the forces and moments on implant abutments for an overdenture were related to the nature of the overdenture attachment system. The study measured the magnitudes of vertical forces and bending moments on the implants as a result of external loading on the implant-retained overdentures. Several trends were observed in the loading on implants and the relationship of that loading to attachment type. In general, the forces and moments on an implant were greater when the external load was applied directly to the prosthesis over the implant or between the 2 implants located in the mid-anterior region. For all the attachments studied, the ZAAG attachment caused the highest forces on the implants for all loading locations on the overdenture. Relatively high moments existed for the ZAAG, NBC, and CK-Ti, which was used as a non-mobile control for the resilient sleeve rings (nitrile and silicone sleeve rings; 2SR90) in the Compliant Keeper System and the other mobile test elements. The smallest implant forces tended to occur with the SEW, SEO, NSB, CK-90, and CK-70 attachments. This result may be attributed to their similar design configurations; both the ERA and NSB attachments are extraradicular stud attachments with resilient caps. While the Compliant Keeper System attachments (CK-90 and CK-70) were used as a splinted bar design, they were related to the ERA and the NSB by virtue of the viscoelastic O-ring housed within the abutment, which acted as a resilient cap.

Both the ZAAG and ERA attachment systems are classified as "universal hinge" resilient attachments for endosseous implants with similar material compositions (titanium nitride keyway component with plastic key components).[21,22] The fact that the ZAAG attachment showed higher forces and moments compared with the other stud attachments could be attributed to its intraradicular design, in which the keyway component is positioned more apical into the implant abutment and closer to the alveolar ridge. The ERA attachments, because of the extraradicular design (with the keyway positioned higher above the implant abutment, above the level of the alveolar ridge), demonstrated lower forces and moments. However, the lower forces and moments might also have come from a different degree of stiffness of the actual plastic components of these 2 systems.

Of the 2 bar systems investigated (the Nobel Biocare bar and clip design versus the Compliant Keeper System bar and clip design), the NBC produced higher forces and moments. It is possible that the lower moments and forces with the Compliant Keeper System could be attributed to the viscoelastic sleeve rings of this system; it has been claimed that this system "works like a resilient ball joint with the sleeve ring damping in all directions (vertical, lateral, and oblique) with a return to passivity when not loaded."[23]

For the NSB as compared to the NB2, there were smaller forces for the NSB when the force was applied over the right and left implants. This could be attributed to the design and material composition of the original standard ball, which has a plastic O-ring housed in a plastic cap, while the newer ball (the 2.25-mm-diameter ball) is made from a metal cap with a spring housed in the keyway component.

Notably, this study was essentially a pilot study whose primary goal was to investigate whether there were significant differences among overdenture attachment systems in terms of load transfer to supporting implants in the same model system. Since only 1 sample of each attachment was tested in the test system, one cannot conclude that a certain attachment will always behave as described in this study. However, it seems reasonable to assume that the attachment components that were tested are representative samples of standardized manufactured components. Therefore, in light of the large differences in load transmission among selected attachment types, it would seem that the results are indicative of the characteristics of the attachments in general. However, further studies of a larger sample of attachments incorporated in more than 1 mandibular model system are suggested for more definitive conclusions. At some stage, in vivo tests would be appropriate as well to examine the influence of variables that cannot be simulated fully in the laboratory, eg, the mechanical properties of the bone around the implants and the properties of the soft tissues that partially support some overdentures.

CLINICAL IMPLICATIONS

The present study has measured the forces and moments on implants and soft tissue for various implant-retained overdenture attachment systems. Based on this limited study, the clinician may be able to make more informed decisions on attachment selection when designing an implant overdenture. A good understanding of implant biomechanics makes it possible to optimize the treatment plan for each patient to reduce the risk of functional complications and failures.[24] Clinically, it could be hypothesized that those attachment systems that provide the most equitable transfer of occlusal forces among abutments are preferred from the standpoint of bone preservation.[11] The levels of force and moment as measured on abutments in this study—typically in the range of 20 to 120 N for forces and 1 to 12 Ncm for moments—occurred during loading of the prosthesis to 100 N. These levels of force and moment on the implants are comparable to those measured in vivo in recent studies with strain-gauged abutments on Brånemark implants in humans.[25,26]

On the basis of the foregoing, the SEW, SEO, or NSB might be selected when designing an implant overdenture retained by free-standing stud-type attachments. Usually this is the most common and most economical design for patients. Of the stud attachments tested, these will provide the lowest forces and moments on the implants and may improve the longevity of the health of the surrounding bone.

When a prosthesis in which the implants are splinted together with a bar is planned, the Compliant Keeper System bar and clip could be selected with its resilient sleeve rings (clear silicone and black nitrile, 2SR90) to provide lower force and moment distribution compared to the Nobel Biocare bar and clip design. This splinted design should be advantageous when the ridge is severely resorbed, since the bar then provides an additional plane of stability. This is because the clip has a sleeve with one end free from any acrylic resin, thus enabling the attachment to rotate around the bar. This action channels the forces to the 2 implants and the edentulous areas when the overdenture is subjected to horizontal forces.[27] These lower forces and moments may also help preserve the health of the surrounding bone.

The implant-retained overdenture provides functional stability and retention, and may also function to maintain bone for retention of the overdenture prosthesis. Therefore, it is important not to violate these principles by placing unfavorable loads on implant abutments. However, at present the amount of force that would be detrimental to the implant and surrounding hard tissues is not well defined. Until such data are available, as a general rule, minimizing of the forces and moments on the implant abutments and surrounding soft tissues to safeguard the longevity and functioning of the implants and the prostheses can be recommended. In addition, future studies that examine the effect of the functional use of these attachments (eg, wear) on the load transfer to the implants and surrounding tissues would likely contribute to the body of knowledge associated with these implant overdentures.

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APPENDIX: FABRICATION AND USE OF ABUTMENT TRANSDUCERS

Fabrication of Abutment Transducers

To measure forces and moments transmitted to the implants from loads applied to the prosthesis, instrumented abutments were utilized. The Brånemark System abutments used in the early portions of this study were strain gauged by Welwyn Strain Measurements, Basingstoke, United Kingdom. Similar strain gauging of the ERA, the ZAAG, and Compliant Keeper abutments was performed by HiTEC Corporation, Westford, MA, according to the following procedures.

On the outside of each abutment, 3 strain gauges, type EA-06-015EH-120, with 120 Ω nominal resistance and 2.0 nominal gauge factor (Micro-Measurements, Raleigh, NC), were attached with the sensing element of each gauge parallel to the long axis of the abutment. The strain gauges were bonded to the abutments at the approximate vertical midpoint of each abutment; the gauges were spaced 120 degrees apart from each other in the horizontal plane of attachment and cemented using M-Bond 600 (Micro-Measurements) adhesive cured for 2 hours at 121°C.

Three lead wires were soldered to each strain gauge. Nylon thread was tied around the top of the abutment above the solder joints to secure the lead wires in place and protect the solder joints. The strain gauges were coated with a protective coating (Gagecoat 8, Micro-Measurements).

Calibration of Abutment Transducer

Prior to using standard Brånemark System strain-gauged abutments as force and moment transducers, calibrations were needed to account for the load sharing between the abutment cylinder and the abutment screw. Note that when a vertical load is applied to the system of the gold cylinder, gold screw, abutment cylinder, and abutment screw, the force is carried down to the implant body partly by the abutment screw and partly by the abutment cylinder. During tests, signals from the strain gauges on the abutments were recorded by a computerized data acquisition unit (Daqbook 100 with DBK 43A strain gauge module, IOtech, Cleveland, OH). The signals were calibrated to measure in strain units by using shunt resistors to create a known Wheatstone bridge imbalance. The calibration that accounted for load sharing was determined according to the following procedure for a Brånemark System abutment transducer. (Other transducers were calibrated similarly, although load sharing was not an issue with the other designs.)

Each abutment transducer was screwed down onto a standard Brånemark System implant with a standard abutment screw tightened to 20 Ncm. Next, a custom "calibration disk" (Fig A1), similar to one used by Glantz and coworkers,[17] was attached to the abutment transducer with a gold screw torqued to 10 Ncm. The disk consisted of a circular plate, cast of silver-palladium, with a diameter of 25 mm and a thickness of 3 mm. This plate contained a Brånemark System gold cylinder in the center, and had several "rests" or depressions located at 5.5 and 10 mm radially away from its center. These depressions allowed forces to be applied to the disk by 3-mm-diameter ball-bearings at 5.5 or 10 mm from the center; this arrangement allowed the application of known moments and forces to the abutment during calibration.

Fig A1 Calibration disk: when attached to the abutment-level transducer, this disk allows for the application of known axial forces and moments to the abutment when known axial forces are applied at known points on the disk.

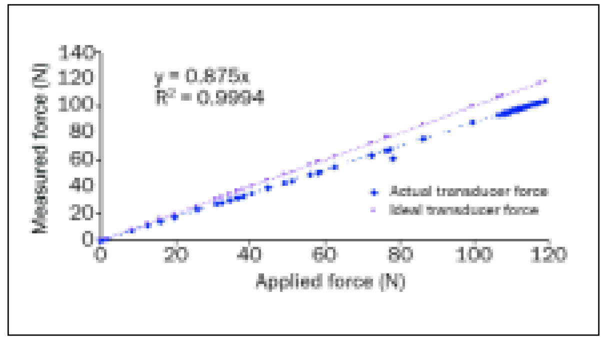

Fig A2 Calibration plot: measured versus applied force for a Brånemark system transducer.

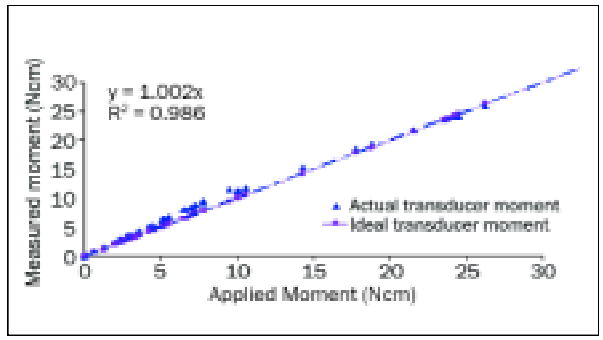

Fig A3 Calibration plot: measured versus applied moment for a Brånemark system transducer.

After the calibration disk was attached to the strain-gauged abutment, the strain signals from the transducers represented the preload in the screw joint of the gold cylinder/abutment system. Since preloads were not of interest in this study, these signals were zeroed off of the strain gauge circuitry. Then, known weights were applied alternately to ball bearings located at the center and radially away from the center on the calibration disk (Fig A1). The strain signals from the transducers were recorded and used to compute the axial force and moment on the abutment cylinder using the following equations originally developed by Tuttle.[19]

$$F = \frac{AE}{3}(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)$$

$$M = \frac{IE}{\sqrt{3}\, r \cos\gamma}(\varepsilon_3 - \varepsilon_2)$$

$$\gamma = \tan^{-1}\left\{\frac{1}{\sqrt{3}}\left[1 - \frac{2(\varepsilon_1 - \varepsilon_3)}{(\varepsilon_2 - \varepsilon_3)}\right]\right\}$$

where F = axial force on abutment cylinder; M = magnitude of moment on abutment cylinder; A = cross-sectional area of abutment cylinder; E = modulus of elasticity of abutment cylinder; I = area moment of inertia of abutment cylinder; r = radius of cross section of abutment cylinder; and ε_1, ε_2, ε_3 = measured strains from strain gauges (ε_1 is the intermediate strain value).

Calibration consisted of comparing the forces and moments computed by the Tuttle equations above with the actual forces and moments applied to the implant. A sample plot from an axial calibration run shows the measured force versus the actual force (Fig A2). The results indicate that the axial force measured by the transducer is 87% of the applied force; this is an indication that the abutment cylinder receives 87% of the applied axial force, while the internal abutment screw receives the remaining 13%. For eccentrically applied loads, it was similarly determined that the transducer also measured 87% of the applied force. Therefore, when Brånemark System transducers are used to measure axial loads, the load determined from the strain gauge readings should be multiplied by a factor of approximately 1.15 (ie, 1/0.87) to produce the actual value of the applied load.

Likewise, a typical moment calibration plot for the Brånemark System abutment transducer is shown in Fig A3. The results indicate a nearly 1-to-1 ratio between the applied moment and the measured moment on the abutment. Therefore, it was not necessary to make any adjustments to the measured moments on the implants as calculated from the Tuttle equations from strain gauge readings.

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