Measurement of the Rotational Misfit and Implant-Abutment Gap of All-Ceramic Abutments

Wael N. Garine, BDS[1]/Paul D. Funkenbusch, PhD[2]/Carlo Ercoli, DDS[3]/Joseph Wodenscheck, MS[4]/
William C. Murphy, MS[5]

Purpose: *The specific aims of this study were to measure the implant and abutment hexagonal dimensions, to measure the rotational misfit between implant and abutments, and to correlate the dimension of the gap present between the abutment and implant hexagons with the rotational misfit of 5 abutment-implant combinations from 2 manufacturers.* ***Materials and Methods:*** *Twenty new externally hexed implants (n = 10 for Nobel Biocare; n = 10 for Biomet/3i) and 50 new abutments were used (n = 10; Procera Zirconia; Procera Alumina; Esthetic Ceramic Abutment; ZiReal; and GingiHue post ZR Zero Rotation abutments). The mating surfaces of all implants and abutments were imaged with a scanning electron microscope before and after rotational misfit measurements. The distances between the corners and center of the implant and abutment hexagon were calculated by entering their x and y coordinates, measured on a measuring microscope, into Pythagoras' theorem. The dimensional difference between abutment and implant hexagons was calculated and correlated with the rotational misfit, which was recorded using a precision optical encoder. Each abutment was rotated (3 times/session) clockwise and counterclockwise until binding. Analysis of variance and Student-Newman-Keuls tests were used to compare rotational misfit among groups (α = .05).* ***Results:*** *With respect to rotational misfit, the abutment groups were significantly different from one another (P < .001), with the exception of the Procera Zirconia and Esthetic Ceramic groups (P = .4). The mean rotational misfits in degrees were 4.13 ± 0.68 for the Procera Zirconia group, 3.92 ± 0.62 for the Procera Alumina group, 4.10 ± 0.67 for the Esthetic Ceramic group, 3.48 ± 0.40 for the ZiReal group, and 1.61 ± 0.24 for the GingiHue post ZR group. There was no correlation between the mean implant-abutment gap and rotational misfit.* ***Conclusions:*** *Within the limits of this study, machining inconsistencies of the hexagons were found for all implants and abutments tested. The GingiHue Post showed the smallest rotational misfit. All-ceramic abutments without a metal collar showed a greater rotational misfit than those with a metal collar.* INT J ORAL MAXILLOFAC IMPLANTS 2007;22:928–938

Key words: *ceramic abutment, metal abutment, misfit, rotational freedom, screw*

[1]Former Resident, Former Gerald N. Graser Fellow, Eastman Dental Center, Division of Prosthodontics, University of Rochester, Rochester, New York; currently in Private Practice, Jupiter, Florida.

[2]Professor, Department of Mechanical Engineering, School of Engineering and Applied Sciences, University of Rochester, Rochester, New York.

[3]Associate Professor, Chair and Program Director, Eastman Dental Center, Division of Prosthodontics, University of Rochester, Rochester, New York.

[4]Technical Associate, Department of Mechanical Engineering and Materials Science, College of Applied Science, University of Rochester, Rochester, New York.

[5]Information Technology Associate, Eastman Dental Center, Division of Prosthodontics, University of Rochester, New York.

Correspondence to: Dr Carlo Ercoli, Division of Prosthodontics, University of Rochester, Eastman Dental Center, 625 Elmwood Ave, Rochester, NY 14620. Fax: +585 244 8772. E-mail: carlo_ercoli@urmc.rochester.edu

The long-term success of implant-supported prostheses in the treatment of the completely and partially edentulous patient has been reported by several authors.[1–5] However, complications have been reported for implant-supported prostheses. Some are specific to the type of prosthesis (acrylic resin fracture in the screw-retained fixed complete denture,[6] attachment adjustment and/or replacement, and rebasing/relining in overdentures,[7]) while certain complications, such as screw loosening and fracture, occur in various types of prostheses.[4,5] Sev-

Presented at the February 2004 American Academy of Fixed Prosthodontics meeting, Chicago, Illinois. Awarded Second Place, Stanley D. Tylman Award.

Presented at the October 2004 American College of Prosthodontics meeting, Ottawa, Ontario, Canada. Awarded Third Place, John J. Sharry Award.

eral investigators have reported a high incidence of screw loosening as the primary disadvantage of single[8–10] and multiple implant–supported prostheses.[3,5,6,11] The primary function of implant screws in single-tooth implant-supported prostheses is to clamp components together (implant-abutment and/or abutment-prosthesis) and not to resist the possible rotation between components. Several techniques have been proposed to avoid screw loosening, such as the use of an antirotational inlay in the screw access hole[12] or a bar to mechanically lock the screw into position,[13] mechanical alterations of the screw access chamber,[14,15] and the use of dental cements in the threads.[16]

New screw designs (Gold-Tite; Biomet/3i, West Palm Beach, FL, and TorqTite; Nobel Biocare, Yorba Linda, CA) have been introduced. The manufacturers claim that the specific plating or coating of these screws allows a decreased friction coefficient of the screw joint components, which increases the preload for a given amount of torque.

Although these screw designs have focused on increasing the screw-joint preload, it is also important to consider that a rotational misfit of the abutment greater than 5 degrees significantly increases the likelihood of screw loosening.[17] Indeed, while 1 study showed that intimate contact between implant and abutment hexagons is not required for screw joint stability,[18] Binon evaluated the machining accuracy and consistency of selected implant components[19] and concluded that intimate machining of the patrix and matrix is essential for antirotational stability.[20] In this study, it was also shown that abutment rotation of less than 2 degrees resists a mean of 6.7 million loading cycles before loosening. In a different study by Binon,[17] a load of 133.3 N was applied in each cycle to reproduce the in vivo vertical occlusal force on a single molar implant. A rotation of the abutment of more than 5 degrees resulted in a 63% reduction in the cycles needed to cause screw joint loosening (2.5 to 1.1 million cycles).[17] Conversely, with no change in rotational fit, but with a change in the design of the abutment screw, there was a significant difference in observed screw loosening,[12] which supports the notion that screw preload also plays a fundamental role in screw joint stability.[18]

Recently, aluminum oxide and yttrium-stabilized zirconium oxide abutments have been marketed. The indications for the use include esthetically challenging areas, such as the maxillary anterior region, where thin gingival tissue and a high smile line are present.[21,22]

The fabrication and preparation of aluminum oxide and zirconium oxide implant abutments require intensive machining, which may increase the time and cost of fabrication. Although the specific steps of the fabrication processes are proprietary in nature, these abutments are generally initially produced in a porous presintered form (referred to as "green") that has decreased mechanical properties and therefore allows for an easier machining process. The abutments obtained are then completely sintered (depending on the material and the technology used) to obtain the final dimensions and mechanical properties. The sintering performed after machining generally entails a certain dimensional change, which is dependent on several variables, including the volume of the object and the specific technology used. This process could result in a lack of consistency in the abutment hexagon dimensions and thus increase rotational misfit.

Therefore, the specific aims of this study were to measure the implant and abutment hexagonal dimensions, to measure the rotational misfit between implant and abutments, and to correlate the dimension of the gap present between the abutment and implant hexagons with the rotational misfit of 5 abutment-implant combinations from 2 manufacturers.

MATERIALS AND METHODS

Commercially available ceramic abutments were used in the study. A metal abutment was selected as the control abutment (Table 1); the manufacturer of this abutment claims that it has less than 1 degree of rotational misfit. Lot numbers for each specimen were recorded. Each group consisted of 10 new specimens.

Measurement of the Implant and Abutment Hexagon Dimensions

Twenty new implants (n = 10, Nobel Biocare; n = 10, Biomet/3i; Table 2) and 50 new abutments (Table 1) were used for this part of the study (n = 10 per group). All implants and abutments were imaged with a scanning electron microscope (SEM; S/240; Leo Microscopy, Thornwood, NY) in a secondary electron emission mode at the beginning and end of the study (before and after rotational misfit measurements) at magnifications of 20× to 127×. To calculate the distance from the center to the corner of the hexagon, x and y coordinates of each implant and abutment hexagon corners were measured with a measuring microscope (Mitutoyo, Kawasaki, Japan) with an instrument error of less than 1 μm by a single investigator and entered into Pythagoras' theorem[23–26] as follows:

$$C\text{-}c = \sqrt{(x_1 - x_c)^2 + (y_1 - y_c)^2}$$

Table 1 Abutment Types, Materials, Manufacturers, and Lot Numbers (n = 10)

Abutment group and codes	n	Material	Manufacturer	Metal collar	Lot
Group 1					
Procera Zirconia (ProZir)	10	Stabilized zirconia abutment	Nobel Biocare, Yorba Linda, CA	None	*
Group 2					
Procera Alumina (ProAl)	10	Sintered aluminum oxide	Nobel Biocare	None	*
Group 3					
Esthetic Ceramic Abutment (EstAb)	10	Sintered aluminum oxide	Nobel Biocare	None	637362
Group 4					
ZiReal (ZiReal)	10	Stabilized zirconia on a titanium sleeve	Biomet/3i West Palm Beach, FL	Titanium	190031
Group 5					
GingiHue post ZR Zero Rotation (ZeroRot)	10	Commercially pure titanium	Biomet/3i	All metal	190236

*There is no lot number for Procera abutments, as they are made to order.

Table 2 Implant Types, Lengths, and Lot Number (n = 10)

Implant	n	Length (mm)	Lot
Nobel Biocare (Brånemark), Yorba Linda, CA	10	18	505478/ 508751/ A002454/ 0052-0047-03/ 501882/504271
Biomet/3i, West Palm Beach, FL	10	10	170740

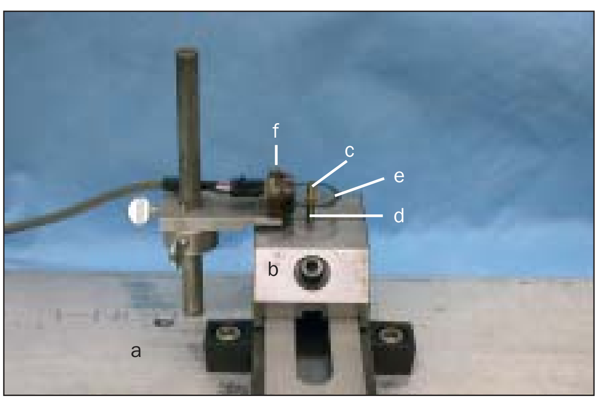


Fig 1 Frontal view of the measuring device. Note the *(a)* metal base, *(b)* holding device, *(c)* abutment, *(d)* implant, *(e)* = Mylar encoder disk, and *(f)* optical encoder.

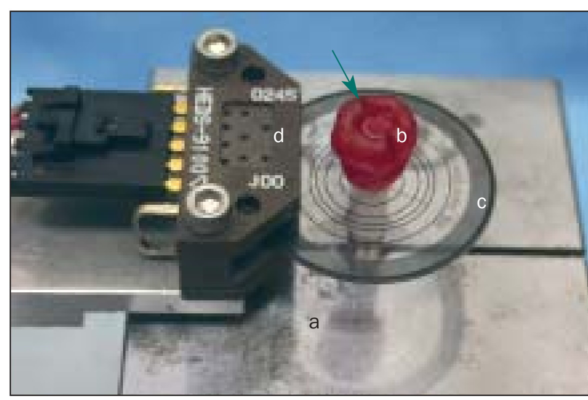


Fig 2 Close-up view of the measuring device. Note the *(a)* holding device, *(b)* ceramic abutment covered with pattern resin (slot made for screwdriver engagement indicated by green arrow), *(c)* Mylar encoder disk, and *(d)* optical encoder.

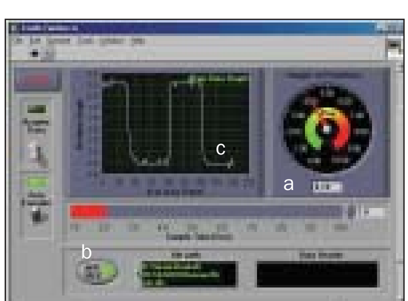


Fig 3 Software interface (VI) on computer screen showing *(a)* the angle of rotation (degrees), *(b)* the sample time (seconds), and *(c)* a raw data graph showing clockwise (downward) and counterclockwise (upward) rotation of abutment.

where C-c was the distance from center to corner of hexagon, x_1 and y_1 were the coordinates of 1 corner, and x_c and y_c were the coordinates of the center of the hexagon.

The center-to-corner distance was the hypotenuse (study variable) of a right triangle, which was determined with the x and y coordinates of the corners (known measures) and the center of the hexagon (obtained by averaging the x and y coordinates of all 6 corners). With this method, the specific position of the implant (or abutment) in the traveling microscope and therefore the fact that the origins of the coordinates were arbitrary had no influence on the center-to-corner measurements (the position of each implant or abutment in the microscope was unchanged during each measurement session).[25]

Measurement of Rotational Misfit and Correlation with the Implant-Abutment Gap

A custom-made metal frame was fabricated to hold the implant-abutment assembly and the angle-measuring device (Figs 1 and 2). Rotational misfit was recorded using a precision optical encoder (HEDS-9100; US Digital, Vancouver, WA) in conjunction with a 1-inch diameter Mylar encoder disk (US Digital). The circumference of the disk was divided into 4,100 distinct segments, creating a "bar code" that the encoder module could read to 0.088 degrees of precision.

A notch was made on the coronal side of each metal abutment (group 5) using a fine disk ("Very-Thin" Discs; Dedeco, Long Eddy, NY). This slot was engaged by a flat-head screwdriver (Alltrade, Long Beach, CA) to rotate the abutments during rotational misfit measurements. The Mylar disk was placed snuggly on each of the abutments. No adhesive was required to hold the disk position on the abutment. For the ceramic abutments (groups 1 to 4), the encoder disk was placed first. Then autopolymerizing acrylic resin (Pattern Resin; GC, Tokyo, Japan) was placed around the coronal end of the abutment. A slot was then made in the acrylic resin to allow engagement by the screwdriver during rotational misfit measurement (Fig 2). A small quantity of lubricant (White Petrolatum USP; E. Fougera & Co, Melville, NY) was applied on the implant prosthetic surface (implant platform) to minimize the friction with the abutment. The abutment was placed on an implant, which was secured to the metal base of the holding device (Figs 1 and 2). The abutment screw was torqued to 1 Ncm, enough to hold the components together while offering minimal resistance to rotation, using a digital torque instrument (Mark 10, Hicksville, NY, accuracy ± 0.35% of full scale ± 1 digit, with 0.1 Ncm resolution).

The abutment-disk assembly was rotated using a handheld flat-head screwdriver (Alltrade) by a single investigator. Before data collection began, each abutment was rotated counterclockwise until binding of the implant and abutment hexagon prohibited further rotation. Data were then collected by turning the abutment first clockwise and then counterclockwise until binding. This clockwise-counterclockwise rotation was repeated 3 times per session for each abutment.

The angle between the clockwise and the counterclockwise positions (rotational misfit) of each abutment was measured on each of the 10 implants from each manufacturer, resulting in 300 measurements for each group of abutments (3 values per abutment × 10 abutments × 10 implants). During the test, each implant was clamped to the metal base and held tightly in position. All abutments from a given manufacturer were tested on 1 implant at a time.

Table 3 Implant Hexagon Center-to-Corner Dimensions in µm

Implant	N	Mean	SD	Min	Max
Nobel Biocare (Brånemark)	60	1.529	0.017	1.463	1.561
Biomet/3i	60	1.540	0.026	1.389	1.587

The principal investigator performed all rotation measurements, while another investigator recorded the implant- and abutment-hexagon coordinates. A pilot test was performed prior to the study to assess the operators' reliability by calculating the rotational misfit of 3 implant-abutment assemblies and the coordinates of the hexagon corners of 3 implants and abutments in each group at 3 different sessions. The reliability of the investigators was found to be excellent ($r = 0.98$ for rotational misfit testing and $r = 0.94$ for x and y coordinates measurement).

Data collection was expedited using a custom-designed computer program (Virtual Instrument or VI) created with a commercially available software (LabView; National Instruments Corp, Austin, TX; Fig 3). The VI scaled the encoder transducers' raw voltage data to degrees of rotation (Fig 3). The VI also saved the rotation angle data into a spreadsheet (Excel; Microsoft, Seattle, WA) for statistical analysis.

The difference between the matrix and patrix center-to-corner distances (also called the gap) was calculated using 2 different methods and correlated with the rotational misfit. The first method consisted of subtracting the mean of the 6 center-to-corner distances of the implant hexagon from the mean of the 6 center-to-corner distances of the abutment hexagon. The second method consisted of subtracting the value of the largest implant-hexagon center-to-corner distance from the smallest abutment-hexagon center-to-corner distance.

Analysis of variance and a Student-Newman-Keuls test were used to identify statistically significant differences in rotational misfit among groups ($\alpha = .05$). Correlation coefficients were calculated to assess a possible correlation between abutment-implant hexagon mean and smallest gaps and rotational misfit. Since it is possible that rotational misfit could occur as a result of implant or abutment machining inconsistency, the correlations between mean and

Table 4 Abutment Hexagon Center-to-Corner Dimensions and Mean and Minimum Abutment-Implant Gaps in μm

Abutment	n	Mean	SD	Min	Max	Mean gap	Smallest gap
Group 1: ProZir	48*	1.612	0.016	1.567	1.648	0.083	0.006
Group 2: ProAl	54*	1.589	0.018	1.548	1.634	0.06	−0.013
Group 3: EstAb	48†	1.604	0.027	1.556	1.671	0.075	−0.005
Group 4: ZiReal	54*	1.575	0.021	1.539	1.653	0.035	−0.048
Group 5: ZeroRot	60	1.57	0.026	1.537	1.747	0.03	−0.05

Negative numbers could represent binding of abutment and implant corners.
*Could not measure all abutments because of instability on the traveling microscope table.
†Two abutments yielded center-to-corner distances that were noticeably erroneous and deemed outliers.

smallest hexagonal gap and rotation were also controlled for each individual implant and abutment (100 combinations per group). No comparative analysis was attempted between the center-to-corner distances of the implant groups (A and B) or between the corresponding measurements among abutment groups. Moreover, although these implant and abutment types are purported by the manufacturers to have the same nominal height and width of the implant hexagon (0.7 mm and 2.7 mm, respectively), crossover testing combining components from different manufacturers was not performed.

RESULTS

Mean measurements of the implant hexagon center-to-corner distances are reported in Table 3, while corresponding values for the abutment groups are listed in Table 4 (n = 10; 6 center-to-corner values per specimen = 60 values per group). No comparative analysis of the center-to-corner distances of abutment or implant hexagons from different manufacturers was attempted.

Due to instability of some abutments on the microscope table, it was not possible to measure the coordinates of 2 ProZir abutments, 1 ProAl abutment, and 1 ZiReal abutment.

The coordinates of 2 EstAb abutments yielded center-to-corner distances that were noticeably erroneous and were deemed outliers. These values and those of the abutments that were not measurable were not included in the analysis (Table 4).

The SEM examination showed that metal mating components (both implant groups and ZiReal and ZeroRot abutment groups; Figs 4 to 6) had generally well defined corners, while all-ceramic abutments (groups 1 to 3) showed less definite angles with relative rounding or flattening of the corner areas (Figs 7 to 9). This relative lack of corner definition of the ceramic abutments was also subjectively confirmed by 1 investigator during the recording of the hexagon coordinates, who found corner identification with the microscope cross-hair slightly more difficult for these abutments. Mean values of rotational misfit are shown in Table 5. All groups were significantly different from one another with respect to mean rotational misfit ($P < .001$), except for the ProZir and EstAb abutments ($P = .4$).

Correlation coefficients showed no significant relationship between the mean or smallest implant-abutment gaps and rotational misfit. Indeed, a relative scattering of the data was noticed when plotting mean gap dimension and rotation values (Figs 10 and 11). However, although scattering was similar for the ProZir, ProAl, and EstAb groups (Fig 10), a specific pattern was observed for ZeroRot abutments (Fig 11b). In this group, gap values were generally distributed only over a range of 20 μm; this group yielded the smallest mean, standard deviation, and minimum and maximum values of rotational misfit (Table 5). When plotting the smallest gap between abutments and implants with the rotational misfit, the same pattern of scattering was maintained in each group, with a general decrease of about 20 to 40 μm in the gap values. The same patterns of data distribution were noted when controlling for individual implant or abutment dimensions (data not shown).

DISCUSSION

The present study partially agrees with a previous study[19] that demonstrated that implant components purported to be virtually identical have a certain degree of inconsistency in the dimensions of the hexagon (Tables 3 and 4). In the current study, however, unlike the aforementioned previous study,[19] the

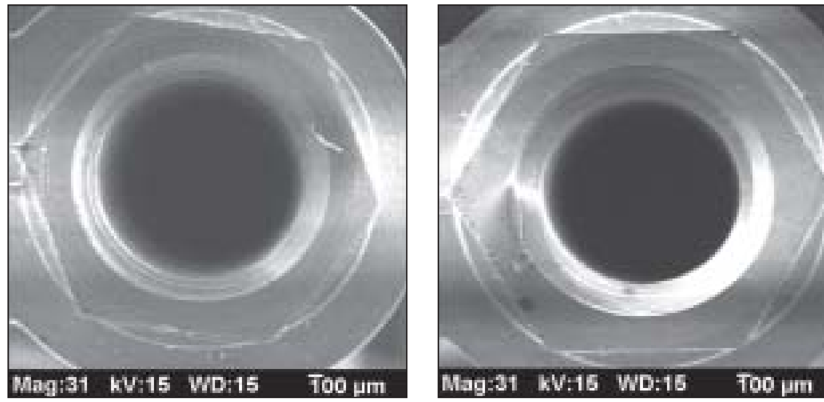


Fig 4 SEM photographs of a Nobel Biocare implant (*left*, original magnification ×31) and a Biomet/3i implant (*right*, original magnification ×31).

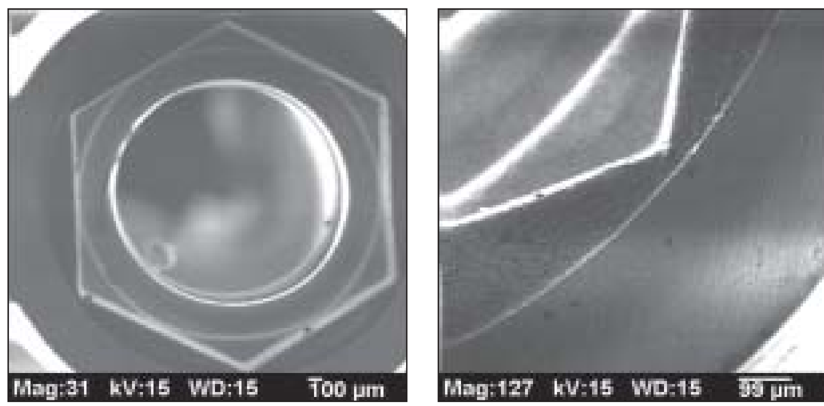


Fig 5 SEM photographs of a ZiReal abutment (*left*, original magnification ×31; *right*, original magnification ×127).

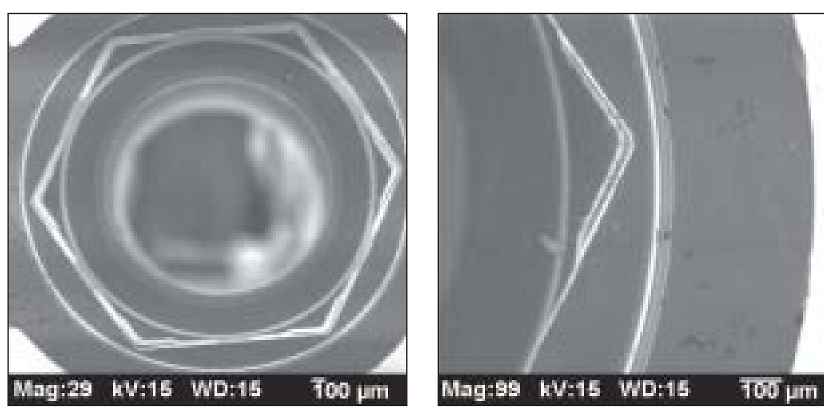


Fig 6 SEM photographs of a ZeroRot abutment (*left*, original magnification ×29; *right*, original magnification ×99; note internal metal protrusion in corners).

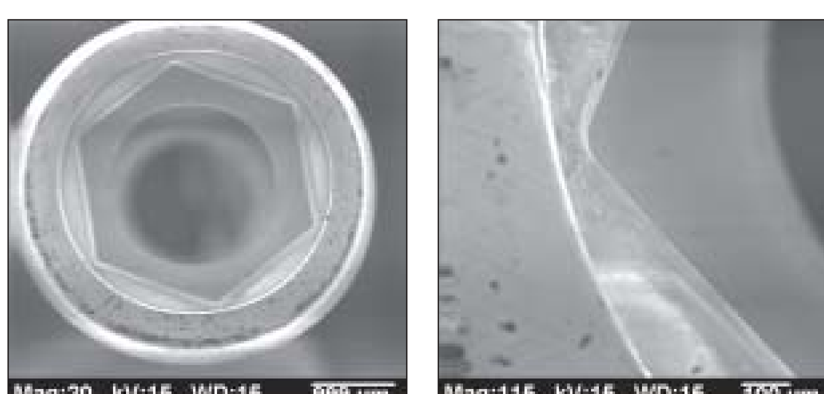


Fig 7 SEM photographs of ProZir abutment (*left*, original magnification ×20; *right*, original magnification ×115; note rounding of corners).

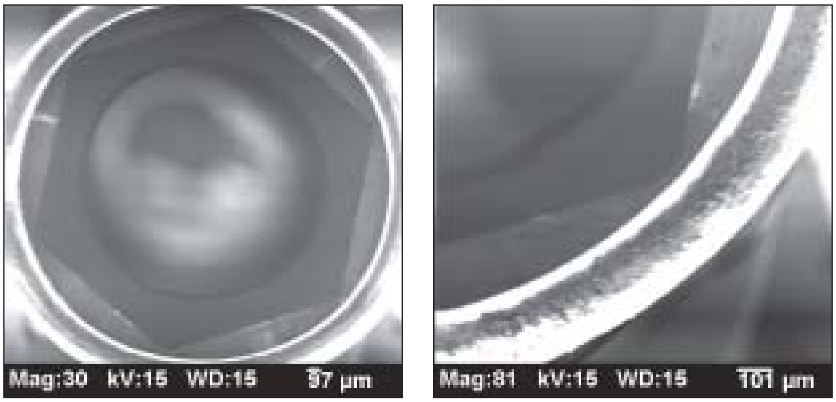


Fig 8 SEM photographs of ProAl abutment (*left*, original magnification ×30; *right*, original magnification ×81; note rounding of corners).

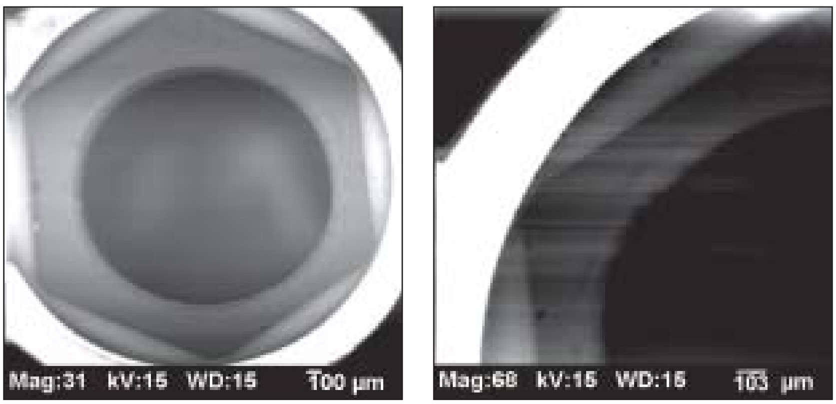


Fig 9 SEM photographs of EstAb abutment (*left*, original magnification ×31; *right*, original magnification ×68).

Table 5 Abutment Rotation in Degrees

Abutment	Mean	SD	Min	Max
Group 1: ProZir	4.13*	0.68	2.59	5.39
Group 2: ProAl	3.92	0.62	2.37	5.39
Group 3: EstAb	4.10*	0.67	1.72	5.82
Group 4: ZiReal	3.48	0.40	1.94	4.74
Group 5: ZeroRot	1.61	0.24	1.08	2.16

*These groups are not statistically different (P = .4). All other groups differed significantly from one another in mean abutment rotation (P = .001).

dimensions of the hexagon were not measured from flat to flat but rather at the corners of the hexagon. Indeed, the gap size (linear misfit) between hexagonal matrix and patrix were calculated from the dimensional differentials of the center-to-corner dimensions of the implant and abutment hexagons. Rotational misfit is controlled by the binding of an implant hexagon corner with a flat of the abutment hexagon. It is possible that the linear distance from the implant-hexagon corner to the flat of the abutment hexagon could have provided a better correlation with the rotation misfit. However, as the distance from corner to flat increases, so does the center-to-corner dimension. Therefore, the authors do not believe that the result would have been significantly different if the gap between the implant-hexagon corner and the flat of the abutment hexagon had been measured.

The method of using an individual to rotate the abutments, as done in this and previous studies,[17,27] might seem arbitrary and subject to considerable error. However, in the pilot study, the reliability of this method was found to be excellent (r = 0.98). Although a completely automated instrument could have been used to rotate the abutments, the potential for greater reliability is uncertain. The instability of some abutments on the microscope table made it impossible to measure the coordinates of 2 ProZir abutments, 1 ProAl abutment, and 1 ZiReal abutment. The reason for the instability of these abutments on the microscope was related to the inability of these 4 abutments to stand vertically on the microscope table with the hexagon area facing upward. The authors speculate that the coronal surface of these abutments was not perpendicular to the long axis of the abutment.

The mean hexagonal rotation exhibited by the ZeroRot abutments was greater than the advertised "less than 1 degree rotation," (mean value = 1.61 degrees; minimum value 1.08 degrees). However, it was significantly less than that exhibited by all other abutments (P < .001). ZiReal abutments, which have a

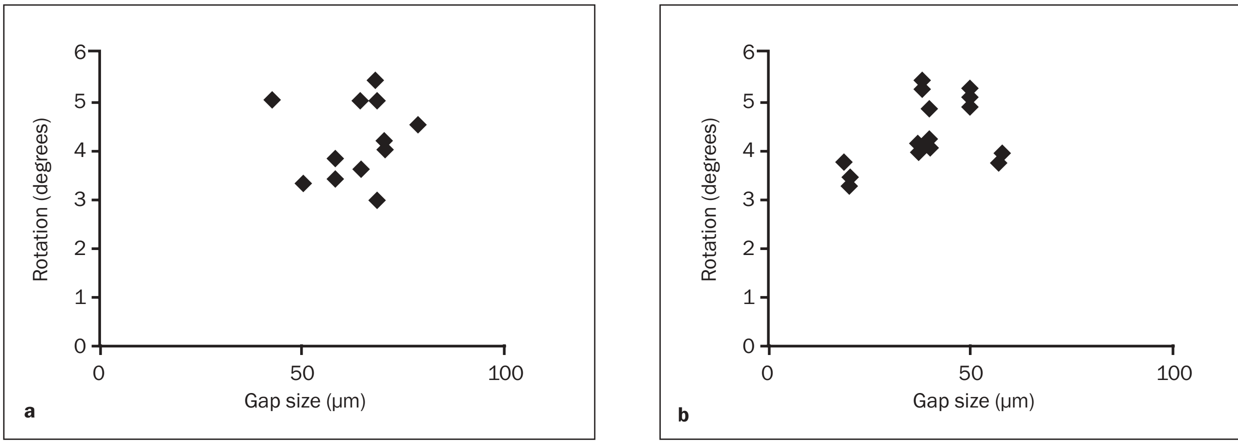
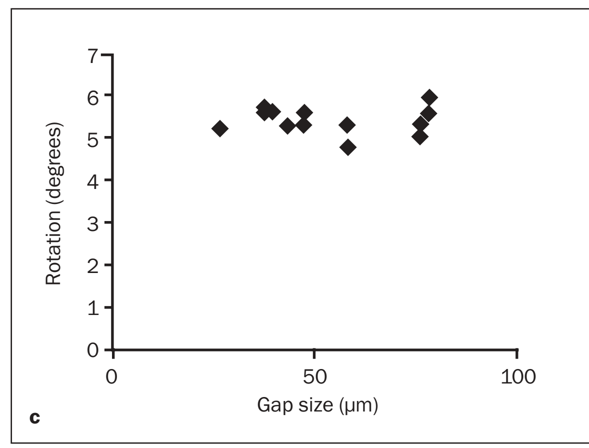


Fig 10 Scatter graphs of the mean gap size (µm) between *(a)* ProZir, *(b)* ProAl, and *(c)* EstAb abutments and Nobel Biocare implants versus rotation (degrees).



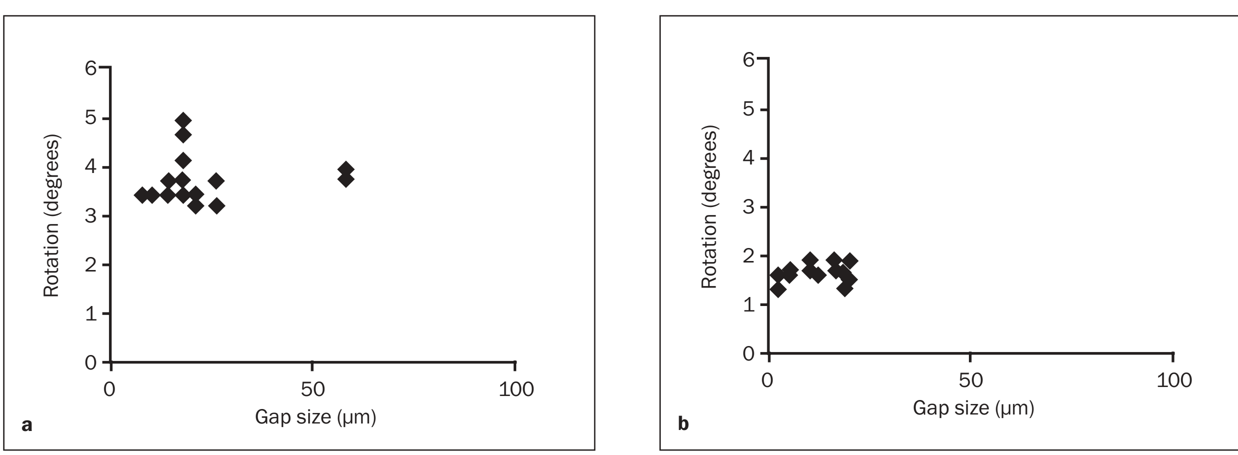


Fig 11 Scatter graphs of the mean gap size between *(a)* ZiReal and *(b)* ZeroRot abutments and Biomet/3i implants versus rotation (degrees).

metal sleeve contacting the implant mating surface, exhibited a mean rotational misfit of 3.48 degrees, while the all-ceramic abutments showed a mean rotation of 4.13 degrees (ProZir), 3.92 degrees (ProAl), and 4.10 degrees (EstAb). In a previous study, it was observed that abutments that exhibited a rotation of less than 2 degrees had the greatest resistance to screw loosening under cyclic loading but that abutments that rotated more than 5 degrees were significantly more prone to screw loosening.[17] Applying these findings to the present study results, the authors speculate that all of the abutments tested in the current study could resist screw loosening up to approximately 4.4 million cycles, with the ZeroRot abutments possibly outperforming the other groups, as it exhibited the least rotational misfit (less than 2 degrees). However, it has also been shown that the presence of an intimate fit between the implant and abutment hexagons might not be the only parameter responsible for screw joint stability.[12,18] Although the importance of an intimate fit has been demonstrated in 1 laboratory[18] and 1 clinical study,[12] Binon demonstrated that the removal of the hexagon from the implant, resulting in 360 degrees of freedom, caused a significant decrease in the number of cycles required to cause screw loosening.

The method of rotating the ceramic abutments involved the placement of autopolymerizing resin on the coronal end of the abutment and the fabrication of a slot in the resin which was engaged during rotational testing. This was done because a previous pilot study demonstrated that, although it was possible to cut a slot in the coronal end of the ceramic abutment, the abutment frequently fractured when rotational force was applied with the screwdriver.

When plotting the data for rotational misfit, significant scattering of the data for ProZir, ProAl and EstAb abutments was evident (Fig 10). Scattering was also observed with the ZiReal-abutment data (Fig 11a). The lowest mean value and least variation for rotational misfit were shown for ZeroRot abutments (Table 5, Fig 11b). This type of abutment is machined to have, at each hexagon corner, an additional metal part that protrudes internally to decrease the center-to-corner distance of the matrix hexagon (Fig 6). This additional feature is most likely responsible for decreasing the linear gap between the matrix and patrix hexagons and providing engagement of the corners of the implant with the abutment (Table 4). Also the smallest gap was calculated for ZiReal and ZeroRot abutments; the negative values exhibited indicate that at least 1 of the corner of the abutment and implant could possibly contact and bind when connected (Table 4). In fact, 1 study[17] suggested that a broad immediate engagement of the hexagon flats between the implant and abutment would be a more desirable feature than corner engagement to resist rotation during cyclic loading. In the present study, no cyclic loading was performed, and it was therefore not possible to assess whether the specific machining features (namely the addition of the internal metal corner) in the ZeroRot abutments could withstand cyclic loading and still provide for a decreased rotational misfit over time.

In another study, the rotation of 5 implant-abutment assemblies was measured, and the rotational misfit ranged from 4 degrees to 6.7 degrees.[19] Although the investigators noted that the abutments had "corresponding variations [to the implant] in size within the abutment matrix hexagonal," the dimensions of the abutment hexagon were not reported. Only the width and height of a standard abutment type were measured. It is clear that, since the gap between the implant and abutment hexagons results from their differential measurements, it is impossible to ascertain whether this linear misfit arises from machining inconsistency at the implant or abutment level. In contrast to the aforementioned study,[19] both the implant- and abutment-hexagon dimensions were measured in the present study, and their differential measurement was correlated to the rotational misfit of the abutment.

While metal abutments and implant hexagons showed distinct and readily identifiable corners (Figs 4 to 6), the all-ceramic abutments exhibited rounding of the hexagon corners, which made identification of the corner slightly more difficult (Figs 7 to 9). Although the variance in linear misfit (gap) could partially be due to greater difficulty in identifying the corner of the hexagon during measuring, it is believed that other factors (eg, the specific fabrication of these abutments) might be responsible for the variance in linear misfit. A possible study limitation, in this sense, is represented by the fact that no Nobel Biocare metal abutments were measured. It is possible that abutments that have a metal fitting surface may exhibit a better fit and more readily identifiable abutment hexagon corners. However, apart from the all-metal abutment (ZeroRot), all of the other abutments are marketed, by their respective manufacturers, with the same indication, namely to be used in areas with thin gingival tissues where the color of a metal abutment could potentially cause a grayness of the gingiva. The authors believe that the inclusion in the current study of abutments with different designs (with or without a metal mating surface) proposed by different manufacturers for the same clinical indication is not actually a limitation of the study but rather a means of comparing and evaluating similar technical solutions. Moreover, the present study is, to the authors' knowledge, the first to independently evaluate the rotational misfit of the tested abutments.

An interesting finding was that there was no direct correlation between the mean gap size (linear misfit) and the mean rotational misfit. This is intuitively surprising when it is considered that a larger gap between the implant and abutment hexagons should allow greater rotation.[17] This is explained by the fact that when an implant and an abutment are assembled together, 6 different gaps are created, 1 for each of the 6 corners of the hexagon. Given the relative inconsistency of implant machining, these gaps would likely have slightly different dimensions. This is why the authors calculated not only the mean gap measurements, but also the smallest gap between the abutment and implant by subtracting the largest implant hexagon center-to-corner distance from the smallest abutment hexagon center-to-corner distance. The rationale for this method of data analysis was as follows. Rotation of the abutment on the implant was limited by the binding of 1 (or simultaneous binding of more than 1) corner of the implant hexagon with a flat of the abutment hexagon. Theoretically, this first corner-to-flat contact will occur in the corners where the smallest gap (best fit) between abutment and implant exists. In the current study, however, the authors did not record the position (out of 6) of the abutment in relation to the implant before testing the rotational misfit. This is a limitation of the methodology, and the authors suggest that additional testing in which the position of the abutment in relation to the implant is recorded before rotational testing is needed to confirm or disprove this hypothesis.

The present study used a torque value of 1 Ncm to secure the abutment to the implant during rotation testing. This torque value does not represent the torque utilized in clinical practice and was selected in a previous pilot study because it allowed unrestricted rotation (until binding of the hexagons) but at the same time maintained the components in contact. Greater torque values were tested in the pilot phase. These greater values allowed only partial rotation of the components, therefore introducing great variability in the recorded rotation values. The SEM images did not show any visible wear of the implant and abutment as a result of multiple screw tightenings, which was likely a result of the low torque application.

CONCLUSIONS

Within the limitations of this study, the following conclusions can be drawn:

1. Machining inconsistency was demonstrated for all implants and abutments tested; the ZeroRot abutment showed significantly ($P < .0001$) smaller rotational misfit than all other abutments tested, although the rotational misfit was still found to be greater than the advertised "less than 1 degree."
2. The presence of a metal collar in the ZiReal abutment improved the rotational misfit when compared to the all-ceramic Procera abutments (Alumina and Zirconia) and the Esthetic Ceramic abutment.
3. There was no correlation between the gap between the abutment and implant hexagons and the rotational misfit.

ACKNOWLEDGMENTS

The authors would like to thank Nobel Biocare and Implant Innovations for providing the implant components. They would also like to thank Ivoclar Vivadent, especially Dr Sebastiano Andreana and Mr Patrick McCabe, for the SEM images.

This study was partially funded by a Stanley D. Tylman student grant from the American Academy of Fixed Prosthodontics and by an Academy of Prosthodontics student grant.

REFERENCES

1. Adell R, Eriksson B, Lekholm U, Brånemark P-I, Jemt T. A long-term follow-up study of osseointegrated implants in the treatment of totally edentulous jaws. Int J Oral Maxillofac Implants 1990;5:347–359.
2. Lekholm U, van Steenberghe D, Herrmann I, et al. Osseointegrated implants in the treatment of partially edentulous jaw: A prospective 5-year multicenter study. Int J Oral Maxillofac Implants 1994;9:627–635.
3. Wannfors K, Smedberg JI. A prospective clinical evaluation of different single-tooth restoration designs on osseointegrated implants. A 3-year follow-up of Brånemark implants. Clin Oral Implants Res 1999;10:453–458.
4. Scholander S. A retrospective evaluation of 259 single-tooth replacements by the use of Brånemark implants. Int J Prosthodont 1999;12:483–491.
5. Jemt T, Lekholm U, Gröndahl K. A 3-year follow-up study on early single implant restorations Ad modum Brånemark. Int J Periodontics Restorative Dent 1990;10:341–349.
6. Hemmings KW, Schmitt A, Zarb GA. Complications and maintenance requirements for fixed prostheses and overdentures in the edentulous mandible: A 5-year report. Int J Oral Maxillofac Implants 1994;9:191–196.
7. Watson RW, Davis DM. Follow up and maintenance of implant supported prostheses: A comparison of 20 complete mandibular overdentures and 20 complete mandibular fixed cantilever prostheses. Br Dent J 1996;9:321–327.

8. Lewis SG, Beumer J III, Perri GR, Hornburg WP. Single tooth implant supported restorations. Int J Oral Maxillofac Implants 1988;3:25–30.
9. Mericske-Stern R, Grütter L, Rösch R, Mericske E. Clinical evaluation and prosthetic complications of single tooth replacements by non-submerged implants. Clin Oral Implants Res 2001;12:309–318.
10. Watson CJ, Tinsley D, Sharma S. Implant complications and failures: The single-tooth restoration. Dent Update 2000;27:35–42.
11. Kallus T, Bessing C. Loose gold screws frequently occur in full-arch fixed prostheses supported by osseointegrated implants after 5 years. Int J Oral Maxillofac Implants 1994;9:169–178.
12. Eckert SE, Wollan PC. Retrospective review of 1170 endosseous implants placed in partially edentulous jaws. J Prosthet Dent 1998;79:415–421.
13. Artzi Z, Dreiangel A. A screw lock for single-tooth implant superstructures. J Am Dent Assoc 1999;130:677–682.
14. Cavazos E, Bell FA. Preventing loosening of implant abutment screws. J Prosthet Dent 1996;75:566–569.
15. Von Krammer R. Procedure for obturating the access canal and preventing the loosening of the abutment screw in an implant-retained fixed prosthesis. J Prosthet Dent 1999;81:234–236.
16. McGlumphy E. Keeping implant screws tight: Are we beyond retrievability? Proceedings of the Fourth International Symposium on Implant Dentistry: Focus on Esthetics. J Prosthet Dent 1994;72:628.
17. Binon PP. The effect of implant/abutment hexagonal misfit on screw joint stability. Int J Prosthodont 1996;9:149–160.
18. Cibirka RM, Nelson SK, Lang BR, Rueggeberg FA. Examination of the implant-abutment interface after fatigue testing. J Prosthet Dent 2001;85:268–275.
19. Binon PP. Evaluation of machining accuracy and consistency of selected implants, standard abutments, and laboratory analogs. Int J Prosthodont 1995;8:162–178 [erratum 1995;8:284].
20. Binon PP, McHugh MJ. The effect of eliminating implant/abutment rotational misfit on screw joint stability. Int J Prosthodont 1996;9:511–519.
21. Yildirim M, Edelhoff D, Hanisch O, Spiekermann H. Ceramic abutments—A new era in achieving optimal esthetics in implant dentistry. Int J Periodontics Restorative Dent. 2000;20:81–91.
22. Prestipino V, Ingber A. All-ceramic implant abutments: Esthetic indications. J Esthet Dent 1996;8:255–262.
23. Harper RJ, Nicholls JI. Distortion in indexing method and investing media for soldering and remount procedures. J Prosthet Dent 1979; 42:172–179.
24. Nicholls JI. The measurement of distortion: Theoretical considerations. J Prosthet Dent 1977; 37:578–586.
25. Nicholls JI. The measurement of distortion: Mathematical considerations. J Prosthet Dent 1978;39:339–343.
26. De La Cruz JE, Funkenbusch PD, Ercoli C, Moss ME, Graser GN, Tallents RH. Verification jig for implant-supported prostheses: A comparison of standard impressions with verification jigs made of different materials. J Prosthet Dent 2002;88:329–336.
27. Vigolo P, Fonzi F, Majzoub Z, Cordioli G. An in vitro evaluation of ZiReal abutments with hexagonal connection: In original state and following abutment preparation. Int J Oral Maxillofac Implants 2005;20:108–114.