Measurement of Misfit at the Implant-Prosthesis Interface: An Experimental Method Using a Coordinate Measuring Machine

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Measurement of misfit at the implant-prosthesis interface is a difficult procedure. One factor common to all methods that attempt to measure 3-dimensional distortion to the micron level is the difficulty in providing verifiably consistent reference points between individual measurement sets. Consequently, the majority of studies use a relative distortion model in which the coordinate reference system is integral to the framework, thus limiting the value of the data gathered. In the method described, the datum plane and the coordinate reference system were set up external to the framework and could be re-established between measurement sets in a verifiable manner. (INT J ORAL MAXILLOFAC IMPLANTS 2000;15:111–118)

Key words: *coordinate measuring machine, datum plane, framework, implant*

Until very recently, contributions to the dental literature[1–7] suggested that a passive fit of framework to abutments was a prerequisite for longevity of implant-retained oral prostheses, although exactly what constituted a passive fit and how to assess it clinically was rarely defined in detail.[8] Indeed, passive fit was described by Tan[9] as "the Holy Grail of the discerning implant prosthodontist." While the well-documented surgical protocol gives a very high success rate in terms of establishing osseointegrated implants, the criteria necessary for the maintenance of osseointegration are less clear. Adell et al[10] stressed the need for atraumatic prosthodontics, ie, a treatment regime in which full attention is paid at all stages to proper stress distribution. A key element was considered to be the lack of passive loading resulting from a misfitting framework. Some authors[11] have suggested that osseointegration is likely to last indefinitely, unless the restoration is overloaded in a manner that compromises the integrity of the interfacial mechanism.

The emphasis on passive fit grew out of the realization that osseointegrated implants present a significantly different clinical mobility, as compared with periodontally supported abutment teeth. While abutment teeth can, to some extent, adjust to a degree of misfit by means of the inherent mobility of the periodontal ligament,[12,13] this is not the case with osseointegrated implants, which can be regarded as ankylotic abutments. Sekine et al[14] found a mobility range of 17 to 58 μm labially and 17 to 66 μm lingually for osseointegrated implants with loads of up to 2,000 g, which they attributed to bone deformation. This is in contrast to the 100- to 200-μm range associated with the periodontal ligament. The presence of less potential for movement could imply that the precision of a cast framework would be more crucial when fixed prostheses are connected to implants.[15] Some publications[16,17] have stressed the need for passive fit of implant superstructures because of the ankylotic character of the implant abutments.

Passive fit implies zero bone strain in the absence of an occlusal load and therefore a requirement for absolute intimate mating of the fitting components. When an ill-fitting framework is connected to

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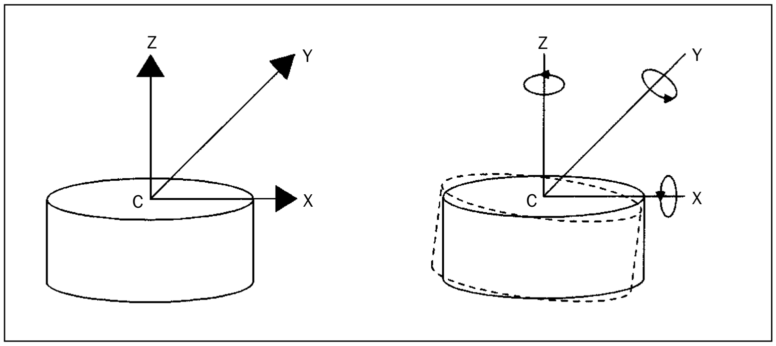

Fig 1 *(Left)* Movement of a given point (C) can be represented in relation to the Cartesian coordinate system. *(Right)* A change in the orientation of the plane formed by the superior surface of a coping can be described in terms of rotation about a given axis. Rotation can occur independent of center point movement.

implants, the forces required to connect the framework will induce bone strain, which is considered to be one of the major reasons for biologic bone response. Passive fit has therefore become synonymous with ideal fit. It is now recognized that absolute passive fit is unachievable[8] and that minor distortion of castings can probably never be avoided.[15] There is a need to develop a definition of what constitutes an acceptable fit in given clinical circumstances.[18]

Despite this body of opinion that promotes passive fit, the role of misfit in the success or failure of osseointegrated implant–supported prostheses is largely unanswered.[18] Although poor fit is widely considered detrimental both in terms of endangering established osseointegration[19] and also in predisposing certain components (retaining screws in particular) to failure,[10,20] few if any studies have been able to show a relationship on a statistical basis.[21] Before any of the myriad of variables that contribute to misfit can be investigated, reliable methods of measuring fit both in the laboratory and in vivo must be developed. Measurement data must also be collected in a manner that facilitates reliable comparison of data between measurement sets.

Distortion can be measured in absolute or relative terms. Nicholls[22] defined these terms as follows: "Absolute distortion involves the measurement of the permanent displacements of the system points with respect to a coordinate system which remains absolutely fixed in space and does not move with the incurred distortion. Relative distortion involves the measurement of the permanent displacements with respect to a coordinate system which moves with the measuring points."[22p579] When comparing measurement sets in which a relative distortion model is used, the value of comparison is limited, since by definition the coordinate reference system has changed and this change is not quantifiable.

Jemt et al[18] reviewed the specific difficulties in determining the validity and reliability of measurement systems when measuring fit at the implant-prosthesis interface, but they did not address the limitations of using a relative distortion model. Carlsson[8] has emphasized the need for a geometric understanding of the problem of measuring fit. He also emphasized the necessity of "consistent references and consistent measuring techniques" if valuable results were to be achieved. Misfit is made up partly of positional error, which can be ascribed to the Cartesian coordinate system (x, y, z), and partly of angular inaccuracy between the mating planes. The problem is one of metrology. To compare individual cylinders, the contact surface must be determined in 6 degrees of freedom, ie, x, y, z coordinates, which can be assigned to individual points, and the angular orientation of the fitting surface in space, which can be related to the chosen coordinate axes (Fig 1).

The purpose of this study was to attempt to overcome some of the difficulties experienced in laboratory measurement of distortion. The aim was to develop an experimental model in which the datum plane and coordinate reference system could be placed external to the framework being measured and to establish consistent references and measuring techniques that were verifiable between one measurement set and the next. To test the model, it was proposed that 2 sets of 5 frameworks each be examined, with each set being identical in its method of manufacture apart from the spruing technique.

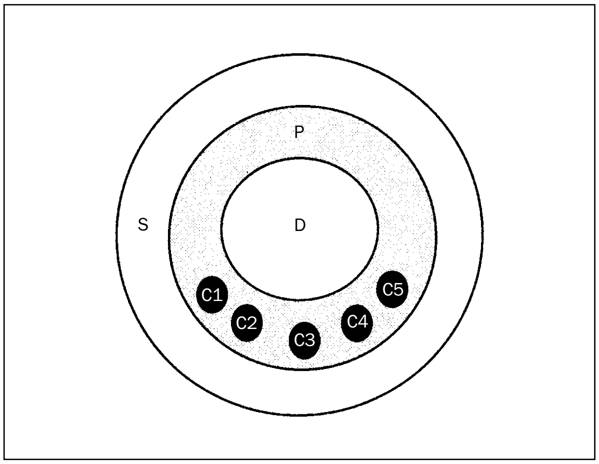

Fig 2a Schematic diagram of master model. P = upper plateau; S = shoulder; D = central depression; C1-C5 = transmucosal abutment positions.

Fig 2b Aerial view of master model.

MATERIALS AND METHODS

Coordinate Measuring Machine

A "moving-bridge" type coordinate measuring machine (CMM) (Eastman Machine Company Ltd, Derbyshire, United Kingdom) was chosen for collection of measurement data, and all measurements were made by the same operator, an experienced CMM machinist. The manufacturers claim a reliability of ± 1 µm for repeated measurements against a known datum. This reflects the inherent accuracy of the machine in well-defined circumstances and cannot be applied to any other measurement setup. The machine consists of a probe, which can be positioned at any desired x, y, z location within the machine's working space. A selection of round, ruby-tipped probes of varying sizes was available for use, ranging from 1 to 4 mm in diameter. The probe tip can approach the surface to be measured in either the z-axis or the x-y plane. When the probe tip touches the surface to be measured, an on/off switching mechanism freezes the reading and allows highly accurate and repeatable measurements of the x, y, z coordinates. Prior to each measuring sequence, the machine is calibrated against a datum sphere of known dimensions, according to the manufacturer's instructions. The CMM was linked to a computer and data handling was carried out by an Axel software program (Axel Systems Ltd, London, United Kingdom).

Master Model

The master model (Figs 2a and 2b) was machined from a cylindrical block of invar, an iron/nickel controlled-expansion alloy (Goodfellow, Cambridge, United Kingdom). All implant components used were manufactured by Nobel Biocare (Nobel Biocare UK, Uxbridge, United Kingdom). The base and upper surface of the block were cut so as to parallel each other. A shoulder was cut alongside the upper surface, leaving an upper plateau, the center of which was machined to give a circular depression, which could later be used as a reference point. Holes were machined in the plateau by a medical engineering company (Implants International Ltd, Cleveland, United Kingdom) using a computer-controlled 5-axis milling machine to accept 5 Brånemark System implants (SDCA 019). The implants were retained with an anaerobic industrial adhesive (Loctite 603, Loctite UK Ltd, Welwyn Garden City, United Kingdom), which is designed for retaining components in close-fitting cylindrical joints. Machining was carried out so that all 5 implants would be aligned in parallel, with their fitting surfaces at the same vertical height from the reference plane and their center points approximately 8 mm apart. Transmucosal abutments (TMAs) (SDCA 005) were then attached to the implants to complete the model. Later in the experimental procedure, it was found that there was a tendency for the TMAs to work loose, and they were subsequently removed and glued in place with a screw thread adhesive (Loctite).

Pattern Fabrication/Casting Procedures

A prototype acrylic resin pattern of a superstructure framework was first fabricated linking 5 gold cylinders. The resin was kept approximately 0.5 mm from both the fitting surface and the upper surface of the gold cylinders. A well was constructed around this pattern from polysiloxane laboratory putty (Coltene,

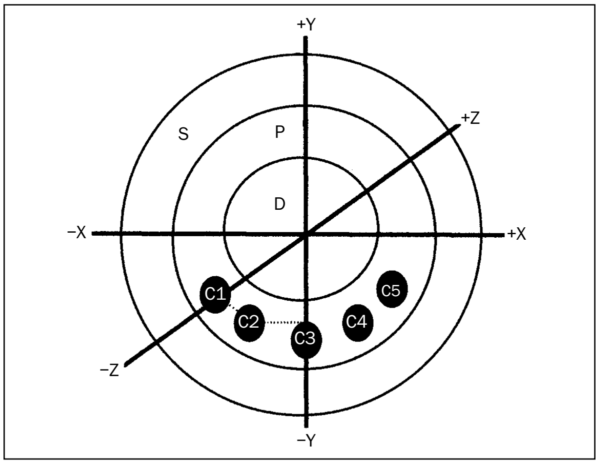

Fig 3 Diagram of the coordinate reference system. The dotted lines indicate how the plane values (ie, the planes formed by the upper surface of the cylinders) are referenced to the coordinate axes.

Altstetten, Switzerland), and a lid was formed over the well. Using a consistent technique, this well was then used to fabricate 10 identical resin patterns. Following fabrication and again immediately prior to investing, each pattern was tested for passivity. The one-screw test as described by White[20] was chosen as a subjective test. Any pattern that failed the test was sectioned and rejoined. All patterns were judged passive prior to casting. Casting in gold alloy was carried out in an identical manner for each framework, apart from the manner of spruing. Five patterns (Group 1) were sprued using a feeder bar system that would result in a connected sprue geometry. The other 5 patterns (Group 2) were sprued to allow for an unconnected ("buttonless") sprue geometry.

Measurement Protocol

The measurement protocol was designed to collect and store centroid and plane data for each cylinder in each pattern (measurement set 1) and casting (measurement set 2).

Centroid Data. Centroid data were collected using the Axel Software "circle" command. "Circle" is a 2-dimensional feature calculated from data points projected onto the datum plane. Calculation uses the least-squares method and can be performed for any number (at least 3) of data points. The center of the circle is presented relative to the reference system, either in Cartesian or polar coordinates. The diameter of the circle is given, and a roundness value is also presented. The roundness value represents the distance from the circle of an additional point measured in millimeters. It is important to recognize that the centroid data do not represent distinct points, but are mathematically calculated values that are then projected onto the datum plane. This is important, because not only is the value itself unlikely to be exactly repeatable, but if the datum plane is not identical between one measurement set and the next, the data will be projected onto different planes and will not be comparable. It is essential that the datum plane be established in a consistent manner before each set of measurements, and that a method of verification be established. When a datum can be established to be identical between measurement sets, it is termed to be "secure."

Plane Data. Plane data were collected using the Axel Software "plane" command. The "plane" feature is a 3-dimensional element calculated from 3 or more non-linear points using the least-squares method. Results are related to the reference system. The z-height of the centroid from the datum plane and a flatness value (f) are also presented. The flatness value represents the distance off the plane of an additional point measured in millimeters. The "security" of the datum is again essential for repeatable plane values between measurement sets. The plane angles are referenced to the coordinate axes.

Datum Plane and Coordinate Reference System. Any measurement set first requires the establishment of a datum plane and a coordinate reference system. The plateau of the master model was chosen for the datum plane. Six probing points were used to define the plane, and the measurement set was accepted if a seventh point was found to give a flatness value of less than 0.003 mm. The y-axis was formed by a line joining the centroid of the central implant (position C3) and the centroid of the central depression. The centroid of the implant was established by probing in the x-y plane immediately below the fitting surface. Three points were used to define the circular shape, and the measurement was accepted if a fourth point gave a roundness value of less than 0.003 mm. The central depression was measured immediately below its rim. Six points were used to define the circular shape, and the measurement set was accepted if a seventh point gave a roundness value of less than 0.003 mm. The x-axis was formed by a perpendicular to the y-axis through the centroid of the central depression. This intersection then formed the origin of the z-axis. The coordinate reference system is illustrated diagrammatically in Fig 3.

Measurement Set 1. Prior to all measurement sessions, the probe was calibrated against the datum sphere, and the datum plane and reference system were established as previously discussed. The data were collected with each cylinder in each of the 10 patterns screwed down on its corresponding abutment. Centroid and plane data were collected for each individual cylinder in each pattern.

Centroid data were collected using a 1-mm probe, and probing was carried out in the x-y plane. The surface probed was the inside of the cylinder immediately below its superior surface. Probing the top ledge of the cylinder in the z-axis could also be used to generate centroid data, but a preliminary trial determined that probing in the x-y plane produced results that were more repeatable. Three points were used to define the circular shape, and a fourth point generated a roundness value. A measurement set was accepted if a roundness value of less than 0.003 mm was obtained. Repeatability of centroid data was assessed by evaluating centroid data generated from 10 individual measurements of a given cylinder. Standard deviations (SD) of 3 µm in the x-axis and 5 µm in the y-axis were recorded.

Plane data were collected by probing the top ledge of each cylinder in the z-axis. A 4-mm probe was used. Three points were used to define the plane, and a fourth point generated a flatness value. The flatness values had a maximum value of 0.00742 mm (only 3 measurements out of 50 had a flatness in excess of 0.005 mm). Repeatability of plane data was assessed as for centroid data. The SD for the x, y, and z plane measurements were 0.162, 0.222, and 0.271 degrees, respectively. The SD for the z-height measurement was 2 µm. The maximum flatness value recorded was 0.005 mm.

The variations in centroid and plane data reflect the inherent accuracy of the CMM, the error in the measurement protocol, and certain manufacturing tolerances of the components (ie, circularity and surface roughness).

The plane and centroid data thus collected were divided into 2 groups. Group 1 composed patterns 1 to 5, and these patterns were cast using a feeder bar spruing system. Group 2 was composed of patterns 6 to 10, and the patterns were cast using a "buttonless" spruing system.

Measurement Set 2. The second set of measurements was made with the individual frameworks in the cross-arch position being screwed down on position C3 (Fig 4). This ensured that the frameworks would be measured in a stress-free state. This arrangement also had the benefit that Cylinder 3 would serve as a control. All data for Cylinder 3 should correspond to the original values if the datum plane and coordinate reference system had been re-established exactly (this assumes that the fit surface and the upper surface of the coping have not been altered geometrically during the casting procedures). This gave the facility to assess the "security" of the datum plane and the coordinate reference system between measurement sets 1 and 2. The centroid data and plane data were collected in the same fashion as before. An analysis of the plane data from measurement set 1 revealed that eliminating data with a flatness value in excess of 0.003 mm reduced the spread about the mean. On this basis, no measurement with a flatness value greater than 0.003 was accepted for plane data unless this did not prove possible after 5 attempts. In these cases, a value below 0.005 was accepted (11 of the 50 measurements had a flatness value greater than 0.003, but of these only 3 exceeded a flatness value of 0.004). Each set of data was gathered in a single measurement session, so that for all frameworks the datum was maintained throughout each measurement set.

Fig 4 Aerial view of a framework in the cross-arch position.

RESULTS AND DATA ANALYSIS

For the analysis of results, exact nonparametric inference tests using the StatXact-3 for Windows program (Cytel Software Corporation, Cambridge, MA) were used.

"Security" of the Datum

Maintenance of the "security" of the datum requires that for C3 the difference between the 2 measurement sets should be 0. The plane values are referenced to both the datum plane and the coordinate reference system and therefore the null hypothesis is that Δx, Δy, Δz, and Δf are 0. The data were compared using the Wilcoxon signed rank test. The analysis indicated no difference between the measurement sets for either group (Tables 1 and 2). This indicates that the datum was maintained and the coordinate reference system was reliably re-established.

Table 1 Two-sided *P* Values for the Comparison of Group 1 Cylinder 3 Data Between Measurement Sets

Plane coordinate	*P* value
X	0.8125
Y	0.4375
Z	0.4375
F	1.00

Table 2 Two-sided *P* Values for the Comparison of Group 2 Cylinder 3 Data Between Measurement Sets

Plane coordinate	*P* value
X	0.3125
Y	0.1250
Z	0.0625
F	0.3125

DISCUSSION

Accurate, reliable, and verifiable measurement to the micron level demands an exacting measurement protocol.[18] Validation of the margin of error in the measurement setup is an essential requirement. Manufacturers of CMM present data for the precision of their measurements against a known datum. This level of precision will not apply to repeated measurements taken from commercially produced components, which will reflect the producers' manufacturing tolerances and be completely meaningless where the coordinate reference system has to be re-established between measurement sets, unless some system of verification is established.

In the interlaboratory repeatability tests carried out by Jemt et al,[18] comparisons were made between 2 optical and 2 CMM-based systems of measurement. The SDs recorded for centroid data in the repeatability element of this study are of the same order of magnitude as those recorded by these authors in their comparison of the 2 CMM-based measuring techniques. The SDs recorded for the plane data were considerably larger than those recorded in their study for the CMM measuring techniques (0.003 to 0.079 degrees), although they are of the same order of magnitude as those measured in the comparison of the 2 optical systems (0.182 to 0.276 degrees). This may reflect the smaller number of probing points used in this study in the determination of plane values.

The literature to date that reports the use of a CMM in the measurement of 3-dimensional distortion uses a relative distortion model.[18,23] This approach limits the value of the data gathered. In the method used by Tan et al,[23] the datum plane(s) and the coordinate reference system were integral to the frameworks. Each cylinder was assigned its own datum plane, and this was not maintained between the measurement sets. In effect, the authors of this study projected their centroid points onto 10 different reference planes. The coordinate reference system was defined as follows: Cylinder 1 was arbitrarily designated as the origin of the coordinate system (ie, 0, 0, 0 point); Cylinder 5 was designated the x-axis (ie, #, 0, 0); and Cylinder 3 was designated as lying in the x-y plane (ie, #, #, 0). Therefore, by definition, the method cannot detect any y-axis or z-axis distortion for Cylinder 5 or any z-axis distortion for Cylinder 3. Data generated on this basis would not provide meaningful information on rotational distortion (rotational distortion was calculated indirectly using an equation requiring z-axis distortion data) or on patterns of geometric distortion. While the authors comment on the extremely small movements measured in the z-axis, they do not acknowledge that this is an inevitable consequence of their method, rather than being representative of actual z-axis distortion.

Numerous papers have been published since 1994 by Jemt and colleagues[15,24–27] detailing results obtained from investigations carried out using a photogrammetric technique for distortion analysis. Collectively, these studies present the largest body of data in publication regarding levels of distortion occurring throughout the whole of the fabrication process. Critical analysis of this work is difficult. According to Hinsken et al,[28] "what is basically needed to use every analytical instrument for close range photogrammetric applications is appropriate software." They add, "Close-range applications present special problems in photogrammetry and therefore specialized software (bundle program) is required." While it is not possible to assess the suitability of the software directly, some areas of concern arise in the use of the photogrammetric technique as described:

1. Lie and Jemt[24] recognize that control of camera orientation is important, but they do not describe how this is achieved. Such control could be expected to be most difficult where intraoral photography is concerned. As these are the only studies to present intraoral measurements, this factor becomes more significant.
2. For photogrammetric techniques to be used in deformation analysis, the datum must be defined. Hinsken et al[28] describe 4 methods available to define the datum; however, it is unclear which was used in the studies in question.

3. The photogrammetric technique involves a number of instruments (camera, stereoscope, analytical plotter, and software program), steps, and procedures, each with the possibility of introducing error. The possibility of a large cumulative error is significant.

In the interlaboratory repeatability test carried out by Jemt et al,[18] the authors stress the difficulties in making reliable measurements at the micron level with these techniques. However, they chose to set up the coordinate reference system in a manner identical to that chosen by Tan et al,[23] thus limiting the value of the data in the same fashion.

The difficulty in establishing reliable reference points and validating measurements is common to all measurement techniques and may be a factor in explaining the rather confusing picture that emerges from various studies. Ness et al[29] found a greater z-axis distortion at the resin pattern stage (5.5 to 9.6 μm) than Tan et al[23] found in the casting process as a whole (0 to 7.1 μm), which would include any distortion from the pattern stage. These authors[23] also found a pattern of rotational displacement of the gold cylinders, while Jemt and Lie[15] found no pattern. The frameworks in the latter study, although they showed greater measured levels of distortion, were considered clinically acceptable, while the majority of those in the study by Tan et al[23] were considered unacceptable.

In the experimental model described, the use of the cross-arch position for measurement set 2 (essential if the frameworks are to be in a stress-free state) demands the availability of sophisticated software for the comparison of the data for cylinders 1, 2, 4, and 5. The data for these cylinders must be rotated back and superimposed on the pattern data to generate an "optimal fit" if values for 3-dimensional distortion are to be generated. The majority of coordinate measuring machines are used in quality control and do not come equipped with such software. This software can be cost-prohibitive, and therefore suitable facilities are unlikely to be available outside dedicated research-oriented metrology laboratories.

CONCLUSION

The presence of a verifiable datum and coordinate reference system should be a prerequisite for any attempt to compare data between different measurement sets. The method as described is a step forward in the measurement of distortion of castings to the micron level because of the following advantages. Both the datum plane and coordinate reference system can be established external to the frameworks, and the reliability of the datum and coordinate reference system can also be monitored between measurement sets. These facilities form the basis of a research tool in which data from measurement sets can be compared with confidence.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the following for their invaluable contribution to this project: Nobel Biocare UK, for donating the implant components; the Department of Systems Engineering, Southampton Institute, Southampton, and in particular Mr David Blackford for providing access to and assistance in the operation of the coordinate measuring machine; and Mr Walter Thomas for his assistance in the production of the frameworks.

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