Comparison of three techniques for measuring wear of dental restorations

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Measurements of impression profiles, profilometer registrations, and scanning electron microscopy (SEM) photogrammetry of metal dies simulating worn restorations were compared as possible techniques for measuring and recording the wear rate of tooth restorations. The results showed that measurements of impression profiles and SEM photogrammetry gave the most accurate results adjacent to regions simulating steep cavity margins, whereas the profilometric technique gave erroneous results in these regions. These errors were related to interference between the conical stylus tip and the steep edges. Moreover, photogrammetry was time-consuming and complex and did not result in better overall precision than with the other evaluation techniques. These drawbacks with SEM photogrammetry were related to complex use of software and low precision of crucial hardware components such as SEM tilt stage and digitizer. □ *Composite resin; computers; photogrammetry; profilometry; tooth abrasion*

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Most clinical wear evaluations of restorative materials have been done by visual examinations or by comparing casts of investigated teeth with reference casts (1–3). During the last few years the reliability of such evaluation procedures has been questioned (4, 5). Other more precise and complex evaluation techniques have also been used (4, 6, 7). These precise techniques use replicas of the restorations and can measure the material loss to within a few micrometers. Unfortunately, these techniques lack the ability to both measure and record the microscopic morphology of the surface simultaneously.

Photogrammetric techniques for obtaining accurate measurements in three dimensions from scanning electron microscope (SEM) photographs have been used for many years (8–15), but their use is still limited. The reason for this is that these techniques are very time-consuming and operator-demanding. Increased accessibility to computers and digitizers should make tedious data accumulation and data processing procedures much more efficient and thus stimulate the use of photogrammetric techniques. Despite these advances, SEM photogrammetry will remain a challenging technique with several associated problems, such as poor electronic stability, lens and cathode-ray tube (CRT) distortions, and poor precision of the SEM tilt stage.

The objective of this study was to determine whether SEM photogrammetry in its simplest form—that is, use of equations based on the parallel projection assumption, visual elimination of lens distortion, and photographic registration on Polaroid film—can be regarded as a useful, or even improved, method for wear determinations of restorative materials.

Materials and methods

A calibration standard sample was made from a brass cylinder, 5 mm high and 10 mm wide, by machining a 3-mm-wide and 500-μm-deep furrow to an accuracy of ±10 μm in its top surface. Eighteen additional samples, each with a furrow cut with a handpiece and a carborundum disc, were made in similar brass cylinders. The furrows on these samples ranged from 2 to 4 mm in width and from ca. 50 to ca. 600 μm in depth.

Two marks spaced 1 mm apart were engraved on each side of the furrow. All measurements were restricted within the boundary of these four marks, and all depth measurements were made from within 500 μm from one of the furrow edges.

Measurements of cross-sectioned impressions

Five impressions (Mirror 3, Kerry-Sybron, Romulus, Mich., USA) were made of the calibration standard sample and 1 impression of each of the additional 18 samples. After setting, each impression was sliced with a scalpel to obtain a thin cross-section within the area marked for measurement. These slices were mounted on individual SEM stubs, plated with Au-Pd, and photographed at a magnification of ×100 in the SEM (JSM-35C, Jeol Ltd, Tokyo, Japan). The depth of each replicated furrow was measured by tracing the photographed profile with the digitizer (IBM 5080 Graphics System, IBM Corp., Armonk, N.Y., USA) interfaced with a computer (IBM 4341 Model 12). The input data were processed with a computer-aided three-dimensional interactive application software (CATIA, Dassault Systems, Paris, France) to produce a graphic output in the shape of the profile. With the software, a reference line, tangential to the flat top surface, was extrapolated over the computer-generated profile, and perpendicular lines were dropped from the extrapolated line at 50-μm intervals (Fig. 1). The distance from the extrapolated line to the bottom of the furrow was computed and recorded along each perpendicular and taken as the depth at that location.

Profilometer measurements

A mechanical profilometer (Surfanalyzer 150, Clevite Corp., El Monte, Calif., USA) was used to record the depth profiles of the furrows of the brass sample specimens. The recording stylus moved at a speed of 254 μm/sec over the surface, and the recorder, to which the output from the stylus was transferred, was set to a resolution of 10 μm/mm.

After the profilometric registrations had been recorded on chart paper, the profiles were digitized and processed with CATIA with the same procedure used for the impression profiles.

SEM photogrammatic determination

SEM photographs of the brass specimens were taken at a working distance of 39 mm

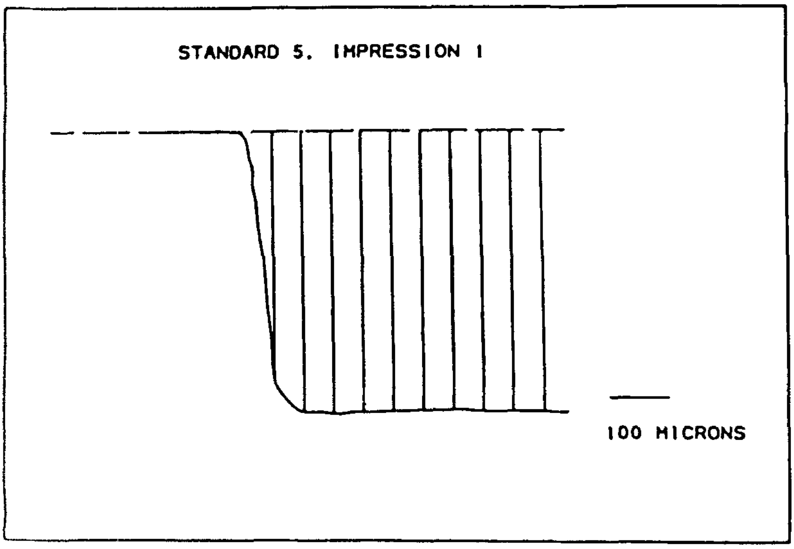

Fig. 1. Profile of recorded furrow adjacent to one of the edges. A line (dashed) has been extrapolated from the top surface over the furrow, and ten vertical lines have been drawn from that line toward the bottom of the furrow. The lengths of these lines were measured to determine the depth at a given distance from the edge.

and a magnification of ×100. A scan rotation and tilt correction unit (35-SRT, Jeol Ltd) interfaced with the SEM was used to fine adjust the tilt axis parallel to the left side of the CRT. The tilt-angle settings used for each stereo pair were 15° and 30°, respectively. The tilt knob was always turned from lower toward higher tilt-angle values to reduce errors due to lag in the stage tilt mechanism during tilt-angle changes. Refocusing was done with the Z-translation knob rather than with the focusing rheostat, to avoid scale differences between the two photographs (14). The photographs were recorded on 100 × 125-mm film (Polaroid 55 Professional, Polaroid Corp., Cambridge, Mass., USA).

All parallax measurements were made with a digitizer pad (Hipad Digitizer, Houston Instrument, Austin, Tex., USA) interfaced with an Apple][e computer (Apple Computer, Inc., Cupertino, Calif., USA). The resolution of the digitizer was 0.125 mm. Software (Topographic Measurement Programs, Scientific Programs, Raleigh, N.C., USA) designed for SEM photogrammetry and using parallel projection was used to capture measurements from the digitizer and to calculate the Z-values (12, 14). The program calculated the X, Y, and Z coordinates for the measured points and saved them on a diskette.

The X-Y-Z coordinate data were transferred to the IBM 4341 computer, which processed the data with a triangulation and contour plotting program (TRICP) to generate a triangulated 3-D mesh from the randomly distributed data points (17). The triangulated mesh was then read into the CATIA program, and with that program the triangulated 3-D mesh could be rotated on the screen so that the profile of the furrow could be viewed (Fig. 2). A reference line tangential to the flat top surface was then extrapolated, and depth measurements were made as described earlier. These measurements were restricted to within 500 μm from the edge because of the limited size of photo overlays per stereo pair.

Digitizer and tilt stage errors

The reliability of the Hipad Digitizer was determined by repeatedly digitizing the length of the scale bar on a photograph of a calibration grid (SPI SEM Magnification/Calibration Mount, SPI Supplies, West Chester, Pa., USA). After each fifth measurement the photograph was removed and positioned at a new pad location, and five new measurements were made. This procedure was repeated five times. The values for the five groups were compared with Duncan's multiple-range test to determine whether different locations on the digitizer gave significantly different values.

To check the accuracy of the digitizer, the digitized values were compared with microscopic measurements (Unitron Universal Measuring Microscope, Unitron Instruments, Inc., Plainview, N.Y., USA) of the same scale bar. The photograph was removed and repositioned after each fifth measurement to determine whether repositioning influenced the microscopic measurements too. These comparisons, between the

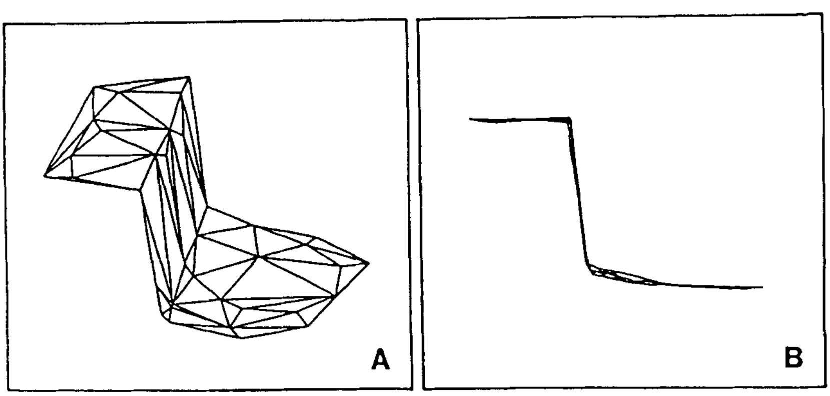

Fig. 2. The figure to the left (A) shows the triangulated photogrammetric values for an edge region displayed by the CATIA software on the computer screen. On the figure to right (B), the edge region has been rotated with CATIA, and the profile is shown.

different 'location' groups, the microscopic measurements and the digitized results, were made with Duncan's multiple-range test (18).

The microscopic measurements of the 100.0-μm scale bar were also compared against the SEM calibration grid. This comparison was done by measuring the length corresponding to 100 μm on that grid at the same time as the previously mentioned 5 × 5 measurements of the scale bar were made.

The 'true' tilt angle for a particular tilt setting was determined by measuring how the projected length of a well-defined distance changed with change in tilt angle (10). The 'true' tilt angles were determined at tilt settings of 15°, 30°, 45°, and 60°, and all these determinations were made at a magnification of ×2000 and a working distance of 39 mm. The length of the projected and photographed distance was measured with the Hipad Digitizer because it was too long to be measured with the measuring microscope.

All changes in tilt angle during these measurements were made by turning the tilt knob from lower to higher values. Each tilt-angle determination was estimated five times on the same photo for five separately projected distances.

Line extrapolation error

The magnitude of the error introduced during the extrapolation of the line tangential to the top surface was also determined. This evaluation was done on the computer-generated profile of the 500-μm standard by drawing what seemed to be the two extreme extrapolation lines for the top surface profile lines. The difference in length from these two lines to the bottom of the furrow at 500 μm from the edge was recorded

Table 1. Digitized scale bar length (mm)

Group order	Mean value	SD	Statistical group
1	10.232	0.552	A
2	10.192	0.1005	A
3	10.212	0.1095	A
4	10.054	0.0538	B
5	10.132	0.0549	AB

and taken as the uncertainty in the depth determination. These measurements were repeated five times for each of the three techniques, and for each of these repeated measurements the computer-generated profiles were regenerated and reorientated. The values of these measurements were then compared (Duncan's multiple-range test) to determine whether significant differences existed between the three measuring methods.

Evaluation of the different techniques

The depth of each sample was measured at 10 different locations with each of the three evaluation techniques. These measurements were made at 50 μm to 500 μm from the edges of the furrows at 50-μm intervals. For the standard with the 500-μm-deep furrow, five such measurements were made independently five times with each of the three techniques.

The depth of each individual location on the 500-μm standard and the pooled mean depth value of the individual locations on both the 500-μm standard and the additional 18 samples were compared (Duncan's multiple-range test) to determine whether local or general differences existed between the three techniques.

Results

Digitizer and tilt stage errors

Table 1 shows how the measured length of the scale bar changed with its location on the digitizer. One location gave significantly lower readings than three other locations. The mean value and standard deviation for all of the 25 digitized measurements were 10.160 and 0.0975 mm, respectively.

The performance of the measuring microscope under similar conditions showed no significant differences between the five groups (Table 2). The mean value and standard deviation for the microscopic determinations were 10.085 and 0.0095 mm, which represent a mean value 0.8% below the digitized mean value. This difference was statistically significant ($P < 0.05$).

Table 2. Scale bar measured with measuring microscope (mm)

Group order	Mean value	SD	Statistical *group*
1	10.091	0.0062	A
2	10.079	0.0133	A
3	10.084	0.0047	A
4	10.084	0.0125	A
5	10.088	0.0068	A

The scale bar generated by the SEM and recorded on the photograph as 100.0 μm actually represented 101.12 μm. Thus, the use of the uncalibrated scale bar resulted in approximately a 1.12% systematic underestimation of the parallax. This error could be even larger, depending on where on the digitizer the measurement was made (Table 1).

The tilt stage setting values compared with the 'true' tilt-angle values demonstrate that the tilt value setting is relatively far from the mean value of the calculated angle (Table 3). This discrepancy is particularly pronounced for the 15° angle value.

Line extrapolation error

The variability in drawing the line tangential to the top surface shows that the lowest variability occurred for the lines drawn on the profile generated from the impression material, whereas no significant differences existed between the two other measuring techniques (Table 4).

Evaluation of the different techniques

Comparison of the three methods on the 500-μm calibration standard sample at specific locations (50-μm intervals) showed that the profilometer technique gave significantly lower values ($P < 0.05$) at distances up to and including 300 μm from the edge (Fig. 3). At 350 μm the profilometer gave a significantly lower numerical value than the photogrammetric technique, whereas the value for the impression technique fell between the values of the two other techniques without being significantly different from these two values. At 400 μm and beyond no significant differences were found between measured values with the three techniques (Fig. 3).

Table 3. Set tilt-angle value versus 'true' tilt-angle value (degrees)

Set value	Measured and calculated	SD
15.0	16.61	1.031
30.0	30.66	0.581
45.0	45.35	0.907
60.0	60.45	0.765

Table 4. Variability in profile line extrapolation (μm)

Measuring technique	Mean value	SD
Photogrammetry	3.4	1.5165
Impression	2.4	0.5477
Profilometer	2.9	1.7464

The standard error for the photogrammetric technique at different local points on the 500-μm standard ranged from 7.01 to 11.24 μm with an average of 8.42 μm. For the impression technique the standard error ranged from 0.58 to 6.85 μm with an average of 2.20 μm, whereas for the profilometer the range was 2.02 to 21.40 μm with an average standard error of 12.77 μm.

Comparison of the pooled mean depth values of the 10 local measurements on each

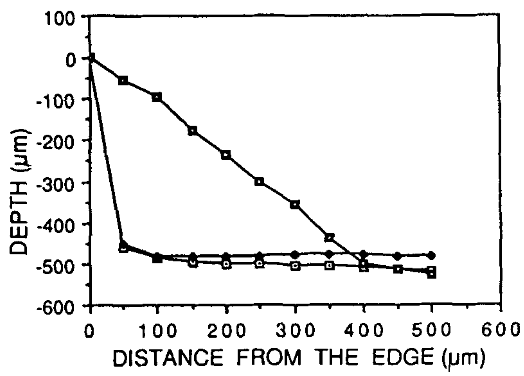

Fig. 3. Depth measurements at 50-μm intervals from one of the edges of the 500-μm-deep standard sample showing the differences between the three techniques—impression measurements (filled diamonds), photogrammetry (unfilled squares), and profilometry (filled squares).

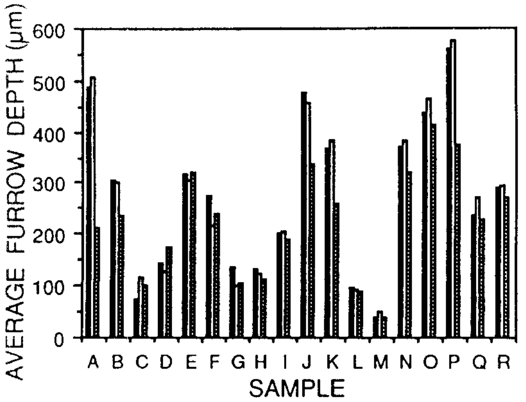

Fig. 4. Bar chart showing the average depth within 500 µm from one of the edges of each of the 18 randomly cut samples measured with the 3 different techniques—impression measurements (filled bars), photogrammetry (unfilled bars), and profilometry (striped bars).

of the 18 samples showed that only particular samples gave significantly different results when the different techniques were used (Fig. 4). Thus, for samples A, J, K, and P the profilometric technique gave significantly lower values than the other two techniques. A characteristic feature of these particular samples was that they all were deep and had almost vertical furrow walls. For samples F and G the photogrammetric technique gave significantly lower values than the other two techniques, whereas for sample H such a significant difference existed only between the photogrammetric and the profilometric determinations. For sample M the photogrammetric technique gave a significantly higher value than the other techniques.

A comparison of the pooled values of all three groups showed that there was no significant difference between the photogrammetric and the impression technique, whereas the profilometer used in this study gave a significantly ($P < 0.05$) lower mean depth value.

Discussion

The results show that most of the photogrammetrically determined values were in relatively good agreement with the values determined on the impressions (Figs. 3 and 4). However, the values determined with the profilometer often deviated considerably from those determined with the other two measurement techniques (Figs. 3 and 4). The tendency for the profilometer to underestimate the depth of the furrow (Fig. 3) was caused by geometric interference between the side of the profilometer stylus and the steep furrow edges. This interference caused the stylus to move upwards adjacent to the edge so that the stylus point could not follow and record the surface accurately in these regions. This error should be characteristic for most profilometer determinations, since several manufacturers of profilometers in the United States claim that most mechanical profilometers have stylus tips with tip angles of 60° or more.

Even though the results indicate that the SEM photogrammetric technique is relatively accurate, the precision of this technique is low when compared with the microscopic measurements of the sliced impressions.

The low precision of the photogrammetric technique compared with the impression technique can be attributed to the poor reliability in both parallax and tilt-angle values (Tables 1 and 3). Of these two variables the most serious offender is the tilt-angle error (Table 3). Since the Z value for a particular point is determined by the formula (12, 14):

$$Z = X_L/\tan(\theta) - X_R/\sin(\theta),$$

where $X_L = X$ coordinate of a feature on left photo, $X_R = X$ coordinate of a feature on right photo, and θ = tilt-angle difference, it is obvious that a large error in tilt-angle difference would have a major impact on the final Z value. This tilt-angle error has also been identified by other investigators as a serious problem with SEM photogrammetry (9). The large standard deviations for the 'true' tilt-angle values are alarming (Table 4). This deviation is related to poor precision in measuring the change in the projected length, which can be traced to the poor precision of the digitizing pad. To avoid this problem, a bench-top calibration of the tilt stage, rather than the method (10) used in this study, is recommended to determine tilt-stage precision.

Another contributor to the lower precision of the SEM technique when compared with the impression technique is that the final depth determinations were made on two-dimensional profiles. For both the impression and the profilometric techniques, these two-dimensional profiles were initially recorded, either on the photograph of the impression profile or on the chart paper. However, for the photogrammetric technique, the generation of this profile was much more complex. Despite the fact that photogrammetric measurements were constrained within a 1-mm-wide band on each sample, the depth of the furrow often differed even over this narrow width. For the photogrammetric technique, this became a problem, since with this technique a three-dimensional mesh model of the region under investigation was first formed (Fig. 2A). To generate the two-dimensional profile, the three-dimensional model had to be tilted and rotated to line up the profile (Fig. 2B). Therefore, owing to variations in depth within the three-dimensional model, multiple profile lines were found on the final profile. Thus, the chance to introduce additional errors with the photogrammetric technique increased when the line serving as the reference for the depth measurements was drawn and the depth values were read.

In addition to the above sources of error, it is also important to mention that the photogrammetric Z-determination used the parallel projection equation rather than the more complex perspective projection equation (12). Because the magnification used was only ×100, one can argue as to whether such a low magnification is suitable for the parallel projection equation. The error caused by using this equation, at least in this study, was insignificant when compared with the tilt-angle error (Table 3). The equation error was negligible because a long working distance was used and a relatively low accuracy (ca 5 μm) was targeted.

Other sources of error for the SEM photogrammetric determination, but not analyzed in this study, are distortions caused by instability of the electronics of the SEM and film distortions. To determine whether these sources were likely to cause major errors, the calibration grid values were compared with their corresponding grid points on photographs taken in connection with the photogrammetric determinations. These comparisons did not indicate that major errors were introduced as a result of scope and film distortion effects.

From a clinical point of view, all the three investigated techniques have advantages and drawbacks. The results show that measurements of ca 1-mm-thick impression profiles gave the most reliable results. Applied to clinical studies, though, this technique should have some potential problems. First, it seems that it would be very difficult to locate slices to the same locations at different occasions during a longitudinal study. Secondly, the most interesting aspect is wear of the complete surface rather than local changes occurring along a line of the restoration. Therefore, to produce a 3-D model with the impression technique, serial sectioning and measurements of each profile would be required. The drawback with such an approach is that the greater the demand for precision becomes, the thinner the slices have to be cut. The drawbacks with this are that thinner slices would increase the risk for distortion and make the technique more time-consuming. Practically, therefore, the use of a profilometer becomes more appealing, since with a profilometer interfaced with stepping motors controlling the location of the sample stage, the whole surface can be automatically recorded with good precision as long as no interference occurs between the stylus and steeply sloping surfaces. Owing to the geometry of most styli, interferences causing erroneous results are likely to occur adjacent to exposed butt-joint margins, but these errors can be avoided or reduced by tilting the sample within the range of the instrument so that interferences can be avoided or reduced.

Of the three techniques, SEM photogrammetry must be regarded as too complex to be regarded suitable for wear evaluations. In addition, the SEM hardware used in this study did not have the precision needed to optimize these measurements. Despite these shortcomings, photogrammetry, especially when used with specially designed cameras, has the potential to become a powerful technique for clinical wear evaluations if knowledge and technology from fields such as computer science and robotic vision are applied to photogrammetry. The progress being made in these disciplines during the last few years makes it realistic to assume that within a reasonable time, cameras will be available which automatically locate identical points on a photo pair, determine their parallax, and then calculate their coordinate values. Having the coordinates available, other software packages can then process the data as outlined in this paper and produce computer-generated surfaces and maps of the surface under investigation. To analyze these surfaces in detail with regard to wear, reference points must be introduced on the surface so that the wear can be related to these points during a longitudinal study. Such reference points could consist of anatomic details, bonded brackets (7), or small groves cut in the enamel (6). Through three of these points a reference plane could then be constructed and used for orientation of the tooth at different occasions. The wear rate could then be determined by calculating changes in the volume between the reference plane and the tooth surface occurring with time. With the presence of such a reference plane it would then be possible to determine both local and general wear.

As a final conclusion, it seems fair to state that, even though this study has identified major limitations and drawbacks with SEM photogrammetry, it seems that photogrammetry in general could have a major impact on future clinical evaluations of wear. It is therefore suggested that more work be done in this field to speed up the development of an automatic photogrammetric technique.

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