Close-Range Photogrammetry with Computer Interface in Dental Research

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ABSTRACT: Four applications in dental research utilizing close-range stereo-photogrammetry with computer interface are described. The applications are (1) measurement of amalgam marginal deterioration *in vivo* in a longitudinal study, (2) root surface measurement of mandibular molar teeth, (3) measurement of movement under occlusal loading of three partial denture clasp assemblies, and (4) occlusal wear of composite materials. In each application, measurements were obtained by using a stereophotogrammetric plotter interfaced with a computer to generate data files for subsequent statistical analysis and report presentation. This paper highlights the computer component used to gather and present the data. The first two applications are described in detail while the last two are presented in abbreviated form.

INTRODUCTION

CLOSE-RANGE PHOTOGRAMMETRY is the science of obtaining three-dimensional measurements from stereophotographs. Certain fields of study in dental research can utilize the advantages of close-range stereophotogrammetry. In our studies, the need for measuring amalgam marginal deterioration, tooth surface area, absolute tooth movement, and composite wear required a precision beyond conventional visual rating systems or other "semi-quantitative" methods. Utilizing close-range stereophotogrammetry adds the capability of measuring quantitatively within a 40 micrometre tolerance range. Clinical stereophotographs are a permanent record from which quantitative data are collected and computed. The interfacing of the photogrammetric equipment with a computer was another requirement because of the vast amount of data which needed to be read, captured, analyzed, and presented.

METHODS

The close-range photogrammetric system included a stereo camera system, Bausch & Lomb 760 Balplex projectors, and a Talos digitizing table interfaced with a Hewlett-Packard 9825T computer. In turn, this was interconnected with a Data General Eclipse 330 minicomputer for data storage and statistical analysis. HASP, Inc. installed the equipment with the associated software modified for close-range stereophotogrammetry and data computation.

The stereo-camera system has two Canon AT-1 35-mm bodies with two matched lenses of a fixed focus. The camera body will accommodate 35-mm film with a lens covering a format of 24 by 36 mm. The image conjugate of each camera is precisely set equal to 55.00 mm, the principal distance of the Balplex 760 projectors (McGivern *et al.*, 1971). The lenses are canted at a six-degree angle to satisfy the Scheimpflug condition. The cameras are rigidly mounted on a common cradle to hold the precisely set exterior orientation. Each camera axis converges at 17 degrees and intersects at a point of best focus for the two cameras. (See Figure 1, camera interior and exterior geometry.) The body of each camera has four fiducial marks to identify the principal point. These fiducial marks are exposed on each film positive.

The relative orientation of the Balplex projectors is fixed and is the same as the relative orientation of the cameras. This is accomplished by setting the Scheimpflug rings at approximately 1.7 on each projector, rotating each projector so that lamphouses are toward the outside, and tilting each projector about its Y axis approximately 17 degrees. Then an exposed pair of 35-mm film positive of a flat grid is centered in the plateholders and projected by the Balplex projectors at a selected magnification factor of eight. This factor was selected because the ratio of the camera object distance (100.09 mm) to the projection distance of the Balplex (760.00 mm) made this ideal (McGivern *et al.*, 1971; Eick *et al.*, 1973; Eick *et al.*, 1976). Therefore, eight times the camera base is the distance between the nadir point of each projector. With the aid of a nadirscope and a calibrated rod, the relative orientation is established. Once the relative orientation has been established, any pair of 35-mm color or black-and-white positives taken with the stereo-cameras and precisely centered with the marked fiducial marks and cross

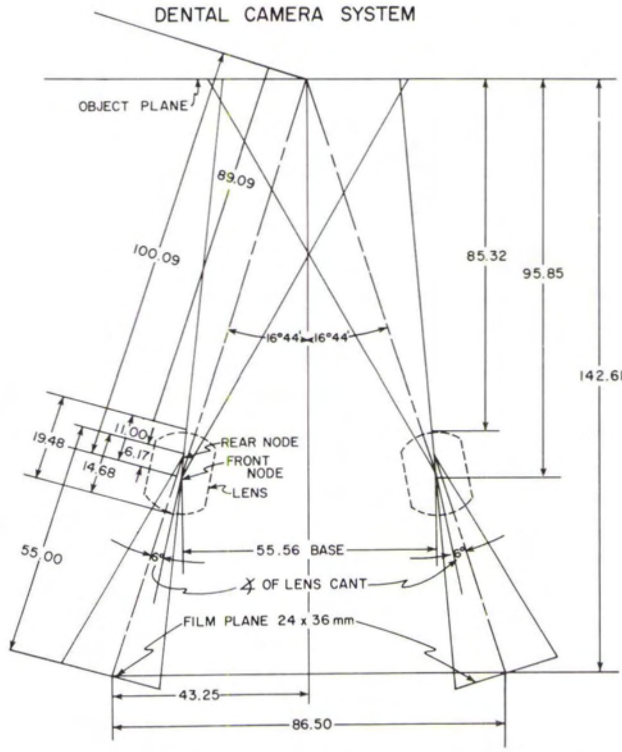

FIG. 1. Camera interior and exterior geometry.

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hairs of the plate holders will produce a parallax-free stereoscopic model (McGivern *et al.*, 1971).

The Bausch & Lomb tracing table cursor electronically reads X and Y coordinates from the Talos table to the nearest 0.025 mm (or ~ 3 μm in real space: i.e., $\frac{0.025 \text{ mm}}{8} = 0.0031$ mm or 3 μm of the projected magnified model). Also, the cursor reads Z positions to 0.0013 mm in real space. These X, Y, Z coordinates are recorded permanently and recalled for calculations in the studies of this paper. The accuracy of the system was determined by photographing an ultraflat grid. Intersections on the grid were read giving X, Y, Z components. From these data a plane in three-dimensional space was obtained with a standard error of ± 20 μm. Depth of focus and precision reading in Z was determined from stereo-pair photographs of a stair-step metal model that could also be measured physically with a micrometer. Depth of focus was 20 mm and precision reading in Z was ± 20 μm.

This paper highlights the computer component of the system used to gather and present the data from four separate dental studies.

RESULTS

Study #1 — Amalgam Marginal Breakdown

The first study was a six-year longitudinal analysis of the marginal deterioration of six different amalgams photographed *in vivo* and measured at three-month evaluation periods in ten patients.

To establish a reference plane for each tooth in the study, an acrylic bite block exposing only one tooth was made. A single surface planar mirror was accurately and permanently set into the bite block to reveal tooth and reference marks scribed in the frame around the tooth.

Features of the stereophotogrammetric plotter/computer system used in this project included the following:

- Using the reference marks to orient each model to a flat plane, baseline stereo photographs could be measured and compared with subsequent time periods.
- Any number of data files could be generated where each file contains data for one tooth for one evaluation period. Our system generated approximately 720 data files (ten patients times six teeth per patient times 12 evaluation periods). Each file typically contained 24 records, each made up of three-dimensional (X, Y, Z) coordinates representing positions on amalgam, ditch, and tooth along a section. Over one megabyte of data was thereby generated.
- As each data file was subsequently processed by a computer program, a one-page printout was made for verification and for a permanent record. Also, a summary record was appended to a summary file used later for data presentation and statistical analysis.
- Several report programs presented and statistically analyzed the summary file. This analysis included T-tests, correlation coefficients, and analysis-of-variance.

Data Acquisition. Three points on typically 24 sections were read on each tooth. Each section could be visualized as a triangle formed by three (X, Y, Z) points read from the amalgam, ditch, and tooth (see Figure 2). The section was oriented from the tooth to the amalgam perpendicular to the ditch. Each of these points was read as an X, Y, Z coordinate within a 40-micrometre reproduceable reading error. These three points, along with the section number, were written to a disk file as one record. Sections were read in consecutive order around an amalgam as determined by the technique and skill of the stereo-plotter operator.

Each data file was named XXYYZZ where XX was the patient case number, YY was the tooth number, and ZZ was the evaluation number in months since the amalgam was placed. One case number approximated 72 files. This scheme for naming the files allowed flexibility in analyzing the data by case number, by tooth number, or by evaluation period.

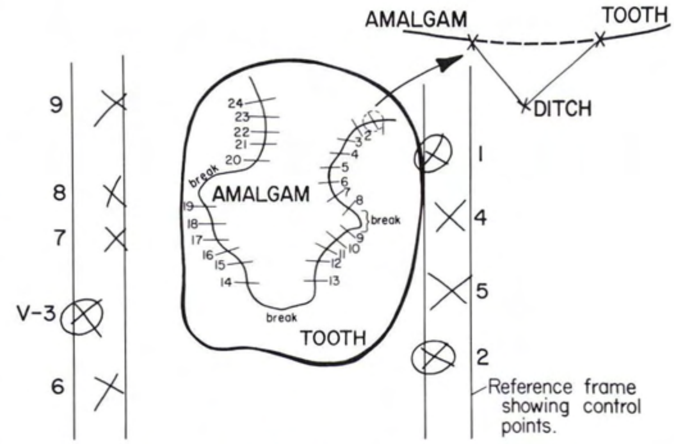

Fig. 2. Typical stereo-plotter view of tooth to be measured.

Individual File Processing. The data files could be processed by a computer program either singly, by all files of a specified case number, or by all files of all case numbers in the entire study. A typical one-page printout is given in Tables 1A and 1B. As shown, each section yields the width and depth of the ditch between the amalgam and tooth. Also, the cross-sectional triangular area formed by the three (amalgam, ditch, and tooth) points is given. The word "break" denotes an irregularity in the usual ordered progression of sections around a tooth. Such "breaks" were necessary when the photograph was poor due to shadows, saliva or glare on tooth or amalgam, or reading from one side of the tooth to the other.

The printout continued with a summary of all the sections. An average width and average depth of the ditch with corresponding standard deviations, the total length of the ditch, the vertically projected area of the ditch, and the volume of the ditch per length were summarized. Figure 3 illustrates the basic geometry for these values.

Consider the three sections in Figure 3. The width of a section is the distance AT. The depth is the distance D. The length between sections is the distance between the mid-points of successive triangular sections. The projected area is the vertically projected area between sections with boundaries defined by the amalgam and tooth points. The volume of the ditch is the volume formed by three successive sections and is given by

$$V = (L1 + L2)\left(\frac{A(1) + 4^{*}A(2) + A(3)}{6}\right)$$

where the area A of a section is given by

$$A = \sqrt{S(S\text{-}D)\ (S\text{-}A)\ (S\text{-}T)} \text{ where } S = (D + A + T)/2.$$

This procedure for measuring volume was verified for the plotter-computer system by measuring standards of known volume.

Summary File Processing. In addition to the printout for each tooth, a summary record was written to a single summary file. Each summary record contained the identical summary data as calculated for the printout plus the identifying case number, evaluation period, tooth number, and the amalgam type (alloy).

Importantly, each summary record also contained the date when it was created. This scheme allows the last summary record generated for a given case number, tooth number, and evaluation period to be processed in subsequent analysis. This was devised to allow re-runs of the same individual data file for many various reasons while not having to re-run all previous individual data files in order to maintain a perfect up-to-date summary file. Also, this feature provided much flexibility in allowing individual data files to be processed in any order.

Statistical Analysis. Data presentation and statistical analysis used the summary file sorted according to the desired result.

TABLE 1A. ONE YEAR STEREOPHOTOGRAMMETRY DATA FOR SYBRALLOY
OUTPUT LISTING OF VOLUME PROGRAM. ALL VALUES ARE EXPRESSED ON A MILLIMETRE BASIS.
PATIENT: 39 TOOTH#: 19 EVAL PERIOD: 12 MONTH ALLOY: S

SECTION	WIDTH OF DITCH	DEPTH OF DITCH	AREA OF SECTION	SECTION	WIDTH OF DITCH	DEPTH OF DITCH	AREA OF SECTION
1	0.197	0.071	0.0070	2	0.230	0.115	0.0132
3	0.144	0.024	0.0017	4	0.193	0.079	0.0076
5	0.206	0.071	0.0074	6	0.219	0.096	0.0105
7	0.436	0.191	0.0417	8	0.298	0.164	0.0244
9	0.367	0.072	0.0132	10	0.254	0.054	0.0069
11	0.096	0.054	0.0026	12	0.198	0.071	0.0070
BREAK							
13	0.269	0.105	0.0141	14	0.222	0.088	0.0098
15	0.528	0.190	0.0502	16	0.256	0.080	0.0103
17	0.147	0.115	0.0084	18	0.305	0.145	0.0221
19	0.256	0.181	0.0232	20	0.128	0.005	0.0003
21	0.216	0.039	0.0042	22	0.356	0.100	0.0178
23	0.275	0.068	0.0093	24	0.237	0.112	0.0132
25	0.154	0.042	0.0032				

SUMMARY OF DATA. PATIENT: 39 EVAL PERIOD: 12 ALLOY: S
AVERAGE WIDTH OF DITCH = 0.247 ± S.D. 0.095
AVERAGE DEPTH OF DITCH = 0.093 ± S.D. 0.049
TOTAL LENGTH OF DITCH = 13.162
PROJ. AREA/MILLIMETRE = 0.2041
VOLUME/MILLIMETRE = 0.01298

TABLE 1B. FIVE YEAR STEREOPHOTOGRAMMETRY DATA FOR SYBRALLOY
OUTPUT LISTING OF VOLUME PROGRAM. ALL VALUES ARE EXPRESSED ON A MILLIMETRE BASIS.
PATIENT: 39 TOOTH#: 19 EVAL PERIOD: 60 MONTH ALLOY: S

SECTION	WIDTH OF DITCH	DEPTH OF DITCH	AREA OF SECTION	SECTION	WIDTH OF DITCH	DEPTH OF DITCH	AREA OF SECTION
1	0.296	0.124	0.0184	2	0.295	0.117	0.0172
3	0.318	0.093	0.0147	4	0.329	0.094	0.0155
5	0.263	0.129	0.0170	6	0.172	0.126	0.0109
7	0.147	0.136	0.0100	8	0.306	0.139	0.0213
9	0.285	0.189	0.0269	10	0.246	0.120	0.0148
11	0.335	0.096	0.0160	12	0.169	0.081	0.0068
13	0.302	0.135	0.0204	14	0.134	0.086	0.0058
BREAK							
15	0.523	0.085	0.0223	16	0.462	0.115	0.0266
17	0.487	0.303	0.0737	18	0.358	0.241	0.0431
19	0.218	0.109	0.0119	20	0.246	0.125	0.0154
21	0.333	0.128	0.0213	22	0.203	0.071	0.0073
23	0.468	0.158	0.0370	24	0.451	0.108	0.0245
25	0.334	0.108	0.0181	26	0.291	0.127	0.0184
27	0.305	0.118	0.0180	28	0.342	0.135	0.0232
29	0.271	0.067	0.0090	30	0.266	0.058	0.0077

SUMMARY OF DATA. PATIENT: 39 EVAL PERIOD: 60 ALLOY: S
AVERAGE WIDTH OF DITCH = 0.305 ± S.D. 0.097
AVERAGE DEPTH OF DITCH = 0.124 ± S.D. 0.049
TOTAL LENGTH OF DITCH = 16.285
PROJ. AREA/MILLIMETRE = 0.2755
VOLUME/MILLIMETRE = 0.01988

These programs were named PSUM.XXX where PSUM indicated "print the summary file" and the XXX represented the type of listing or statistical test. A list of programs and their functions is given in Table 2.

STUDY #2 — ROOT SURFACE MEASUREMENT OF MANDIBULAR MOLAR TEETH

The purpose of this second study was to determine if a significant difference exists between the surface areas of the mesial and distal roots of mandibular first molars (Anderson *et al.*, 1983). Such information is useful in determining which root to retain when root amputation or hemisection procedures are considered.

Ten mandibular first molars were hemisected and the root surface of each root was measured using stereophotogrammetry and computer analysis. In each tooth the mesial root was determined to have a greater surface area than the distal root. This difference was found to be statistically significant.

No information existed in the dental research literature about the comparison of the surface areas of mesial and distal roots of the same tooth. An accurate method of measuring root surface area using stereophotogrammetry and computer analysis was developed.

Procedure. The stereophotogrammetry system required stereo photographs of each tooth to be analyzed. The root surfaces were demarcated with pressure-sensitive tape into five sections

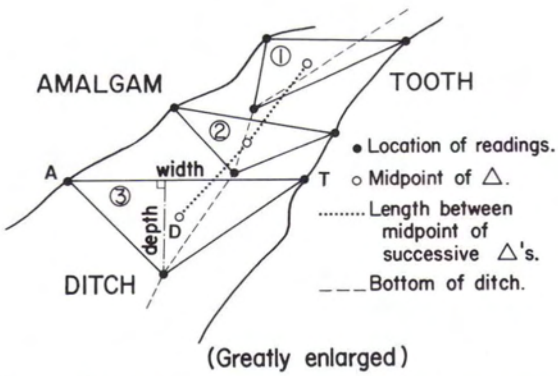

FIG. 3. Schematic view defining amalgam, ditch, and tooth measurements.

TABLE 2. PROGRAMS AND THEIR FUNCTIONS

PROGRAM	FUNCTION
PSUM.PAE	List summary data by Case#/Alloy/Eval Period
PSUM.EAP	List summary data by Eval Period/Alloy/Case#
PSUM.ANOVA	Prints analysis of variance of summary data by Evaluation Period
PSUM.TTEST.EVAL	Prints T-tests of summary data by Eval Period
PSUM.TTEST.CASE	Prints T-tests of summary data by Case#/Eval Period/Alloy Pairs
PSUM.CORR	Prints correlation coefficients by Case#/Eval Period/Alloy between width & depth

(mesial, distal, buccal, lingual, and apical). Stereo color photographs of each section of each root were then exposed using a stereo camera system.

The processed transparencies were projected, resulting in an image magnification of eight times. The X, Y, Z coordinates were taken from the projected image at 5-mm increments (0.625-mm increments on the actual tooth root surface).

These data were entered automatically into data files in the computer.

Computer Analysis. Computation was based on calculating the area of a four-sided figure sectioned into two triangles. From the *X, Y, Z* coordinates given for the four vertexes of this figure, the area of the first triangle was calculated from the length of its sides as

$$\text{Area} = \sqrt{S(S-A)\,(S-B)\,(S-C)}$$

$$\text{where } S = (A + B + C)/2$$

$$A = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2}\,,$$

$$B = \sqrt{(X_1 - X_3)^2 + (Y_1 - Y_3)^2 + (Z_1 - Z_3)^2}\,, \text{ and}$$

$$C = \sqrt{(X_2 - X_3)^2 + (Y_2 - Y_3)^2 + (Z_2 - Z_3)^2}\,.$$

The area of the second triangle was similarly calculated. Calculations continued until the area of the section was determined. This process was repeated for each section of a root. The tooth surface area of a mesial or distal root was calculated by adding the various sections.

Before this method for calculating surface area was accepted, standard geometric shapes with known surface area were analyzed to test the accuracy of the stereophotogrammetry and computer system. A square, cylinder, and sphere were used as these standards. The stereophotogrammetry and computer system were at least 99 percent as accurate as methods used to measure width and length, such as measuring microscope (0.02-mm divisions).

A one-centimetre square of graph paper was folded in half. Two different orientations in space were analyzed and found to be within 7 percent of the true surface area. Allowing a ± 0.3-mm error in reading the boundary (the width of a sharp pencil line), both calculations were within the reading error of the true value. The difference in the two readings was 1.08 percent.

A metal rod of 9.6-mm diameter and 6.5-mm length was used as the cylinder standard. The rod was marked off in four sections and each section was analyzed as a separate surface. The total area was determined to be 98.45 percent of the true known area.

A ping-pong ball of 37.34-mm diameter was marked into eight sections and used as the sphere standard. One of the sections was analyzed with the result that 99.5 percent of the true area was measured. Again, error in measuring the diameter and sectioning was exactly one-eighth of the sphere introduced error.

In testing a "mathematical" sphere to verify the computer program accuracy (but not the stereophotogrammetry system), only approximately 100 triangles were required to calculate 99 percent of the true area of the sphere. Typically, 1,000 triangles were used to calculate the surface area of each root.

Statistical Analysis. Even though the distal root of mandibular molars appears visually to be the larger root, this study demonstrated that the mesial root has the greater surface area in each tooth studied. This difference was statistically significant ($p < 0.05$) when tested using a t-test for paired varieties. Table 3 summarizes the data.

STUDY #3—MEASUREMENT OF MOVEMENT UNDER OCCLUSAL LOADING OF THREE PARTIAL DENTURE CLASP ASSEMBLIES

The third study using close-range stereophotogrammetry with computer interface involved measuring movement of three different types of partial denture clasp assemblies subjected to controlled vertical loading (Browning *et al.*, 1982, 1986a,b, 1987; Eick *et al.*, 1987).

A number of research efforts have been aimed at determining which type of clasp assembly does, in fact, cause the least amount of movement of abutment teeth. Several different methods of measuring this movement have been used but often with inconclusive and sometimes contradictory results. The three-dimensional technique afforded by stereophotogrammetry with computer interface yielded definitive quantitative results.

Procedure. An Instron testing machine (Instron Corp., Canton, Massachusetts) was used to apply uniform loads perpendicular to the occlusal plane of the partial denture under test. This loading was done through a stainless steel ball placed in a dimple on a specially constructed loading platform to insure repeatability for all tests.

Each partial denture was initially seated with a 30-kg load. During loading, stereo photos were made at 0, 10 kg, 20 kg, and 30 kg. The stylus of the Instron was then raised, the partial denture was removed from the test model, then replaced and

TABLE 3. ROOT SURFACE AREA MEASUREMENTS (MM^2).

Mesial root	Distal root	Total mesial + distal	Difference* mesial − distal	Percent difference distal/mesial × 100
212.8	204.0	416.8	8.8	96
267.8	249.3	517.1	18.5	93
229.8	203.2	433.0	26.6	88
223.0	181.7	404.7	41.3	81
275.3	236.2	511.5	39.1	86
223.5	187.2	410.7	36.3	84
264.5	232.1	496.6	32.4	88
312.2	282.4	594.6	29.8	90
284.0	226.0	510.0	58.0	80
226.5	183.6	410.1	42.9	81
Average				
251.9	218.6	470.5	33.4	87

*t-test for paired variates, $p < 0.005$ (Anderson *et al.*, 1983).

seated with a 30 kg load, and the process was repeated until three were made for each framework at four loads: 0, 10 kg, 20 kg, and 30 kg.

Data Acquisition. The stereo photos at each load level were taken and subsequently analyzed, using the stereophotogrammetric plotter coupled to the computer for data storage. The movement in the buccal-lingual (X), mesio-distal (Y), and the occlusal-apical (Z) directions was measured. In addition, the total movement as expressed by the three-dimensional summation vector, independent of direction, was calculated.

A data file was created for each loading test. Each record in the file contained up to 20 reference points (for orientation of the plotter), ten tooth points, and ten clasp points. A one-page printout for each file was generated for verification of data and to provide a hard copy.

Statistical Analysis. The data were analyzed using a t-test, $p < 0.05$. Two results of the study revealed that clasp assemblies moved more than their abutment teeth and the design of the clasp assembly did not generally affect the direction of movement (Browning *et al*., 1986a; 1986b.

Study #4—Posterior Composite Wear

The purpose of this study was to adapt the stereophotogrammetry method to measure the clinical wear of posterior composites (Eick et al., 1984; Eick et al., 1985).

In this application, the stereo-cameras and reference system were modified to incorporate the use of a bite splint and mirrors attached directly to the cameras.

The computer program developed for this study determined directly from the stereophotogrammetry measurements volume change versus time. The computer program was verified by using a segment 9.8 mm long and 1.8 mm deep. This method determined the volume of the standard to an accuracy of 2 percent. Repeated volume measurements produced a coefficient of variation of less than 0.3 percent.

The program used to read data at successive time intervals has the feature of presenting the original baseline orientation and readings to the stereo-plotter operator. The operator is then able to take readings of a composite from year to year within the same frame of plotter reference. This method insures the data may be directly compared among different time periods to a high degree of accuracy.

The procedure of measuring posterior composite wear is now being applied in ongoing clinical research projects.

CONCLUSION

The significant results presented in this paper were made possible by using close-range stereophotogrammetry with computer interface in dental research. The ability to measure known geometrical standards to a high degree of accuracy with the combined system provided confidence for the results obtained in the four applications discussed in this paper.

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