Quantitative Radiographic Measurement of Dentinal Lesions

T.J. HEAVEN, A.R. FIRESTONE, and F.F. FEAGIN[1]

University of Alabama School of Dentistry, and [1]Department of Physiology and Biophysics, UAB Station, Birmingham, Alabama 35294

The purpose of this investigation was the comparison of the precision and accuracy of two reference ramp techniques for the quantification of radiographic density changes in teeth. Radiographs (65 kVp, 10 ma, 1 s, and intra-oral ultraspeed film) of transverse sections from extracted permanent human molars were made before and after dentinal lesions were created. Each radiograph contained the image of a tooth section and the aluminum reference ramp. Method A used the image of the ramp on both the before- and after-lesion radiographs, and method B used the image of the ramp only on the before-lesion radiograph. Three groups of lesions (0.525-mm diameter, n = 11; 0.675-mm diameter, n = 9; and the 0.525-mm holes enlarged to 0.675 mm) were measured radiographically by each technique and by direct planimetry of the lesions. Radiographic method B produced results in close agreement with the planimetric measurements. Method B differentiated ($p < 0.05$) between groups that had a mean planimetric size difference of 0.10 mm (equivalent to a change in density difference of 0.6%). These density change measurements are in absolute units of mm of aluminum that can be compared between lesions and between samples. This technique may prove useful for the quantification of changes in mineral density of caries lesions detectable in longitudinal radiographic records.

J Dent Res 69(1):51–54, January, 1990

Introduction.

Substantial resources of time and money are being expended in the diagnosis and treatment of approximal caries. The primary diagnostic tool for the evaluation of the approximal surfaces of posterior teeth for caries is the bitewing radiograph. Based on surveys of dental services rendered (ADA, 1979a) and fees (ADA, 1979b) charged in the US during 1979, it is estimated that 121,509,000 bitewing radiographic examinations were performed at an approximate cost of $1.4 billion. During the same period, two- or three-surface amalgams, the most common restorative treatment for approximal caries, were placed at an estimated cost of $2.1 billion.

Several approaches to scoring or quantifying the extent of the image of approximal caries lesions on bitewing radiographic films have been utilized. Investigators have commonly scored the degree of penetration toward the pulp on multi-point scales that are based upon anatomical divisions of the radiographic image of the approximal enamel and dentin. These penetration measurements have been compared with direct examination and histological findings (Marthaler and Germann, 1970; Gwinnett, 1971; Mejàre *et al.*, 1985), and they have also been used for estimation of the rate of initiation of new caries lesions and the progression of existing lesions (Espelid, 1986; Shwartz *et al.*, 1987; Pitts, 1983). Others (Shepherd, 1945; Rekola, 1987) enlarged the radiographic image by projection and measured the area of the lesion planimetrically. Muhler *et al.* (1967) monitored the progression of approximal lesions by weighing paper cut-outs of such projected images of lesions.

Computer-based image processing and analysis have recently been applied to the examination of dental radiographs. Gröndahl *et al.* (1983) applied an image-processing technique known as subtraction to the detection of bony changes in the periodontium. Pitts (1984) reported a technique that utilizes image analysis for approximal lesion detection and area measurement. Ruttimann *et al.* (1986a) described a method for volumetric estimation of bony periodontal defects by reference to a wedge of cortical bone. Vos *et al.* (1986) reported a method for estimating the volume of aluminum cylinders inserted in periodontal bone, relative to a reference wedge of aluminum.

The aim of this study was to compare two reference ramp techniques for quantitative radiographic density measurements with the actual size of artificial dentinal lesions through the application of computer-based image processing and analysis.

Materials and methods.

Eight transverse sections from the middle third of extracted human permanent molar teeth were radiographed before and after two different-sized dentinal lesions were created, by holes being drilled parallel to the long axis of the tooth. The samples had a mean (±S.D.) axial height of 3.11 (±0.30) mm, and a mean maximum bucco-lingual dimension of 9.64 (±0.83) mm. The sample and the aluminum ramp (3.20 mm thick, 14.86 mm high, and 23.84 mm long) were in contact with the film packet (Fig.). The initial 0.78 mm was removed from the thin end of the ramp, two layers of lead foil were glued to the sides and the tall end of the ramp, and a coat of radiopaque paint was applied to the thin end of the ramp. This was done so that the contrast at the periphery of the ramp's image on the radiograph would be increased and the effects of point source radiation on the image of the ramp would be reduced. The same ramp was used for all the radiographs in this experiment. The exposure settings of the x-ray unit (Model 1000 Intra Oral X-Ray System, General Electric, Milwaukee, WI) were 65 kVp, 10 mA, and 1 s. The target-to-sample distance was 55 cm. All films were developed in an automatic processor (Model 081, Hope Industries, Willow Grove, PA). Thus, the radiographic image of a sample and the aluminum reference ramp were on each film (intraoral ultraspeed DF-58, Eastman Kodak, Rochester, NY).

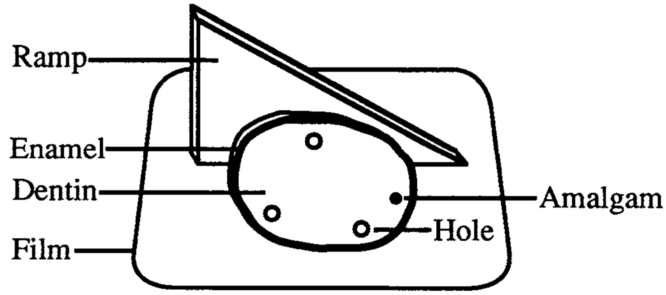

Fig.—Radiographic set-up of aluminum reference ramp and transverse tooth section with artificial dentinal lesions (holes) and amalgam (see text) positioned on film packet. The primary x-ray beam is perpendicular to the plane of the film.

Received for publication May 25, 1989
Accepted for publication August 2, 1989
This investigation was supported in part by NIDR Grant 06951.

Three groups of lesions were compared: Group one (0.525) consisted of 11 axial holes created in four samples with a 0.525-mm dental pin drill (Kodex, Whaledent International, New York, NY); group two (0.675) consisted of nine holes created in five samples with a 0.675-mm drill; and group three (0.675E) consisted of the holes in group one enlarged with a 0.675-mm drill after the radiographs for group one had been taken. All the holes extended through the axial height of the samples. Before the samples were radiographed, a small restoration of amalgam was placed in each sample. This filling served as a reference so that alignment of the images for subtraction could be facilitated. The buccal or lingual surface of each sample was flattened to provide a rest surface for reproducible orientation of the sample for each radiograph. The radiation passed through the samples in the bucco-lingual direction, producing a radiographic image similar to a bitewing radiograph of a molar with a lesion confined to the dentin.

The image of the radiograph was captured by a monochrome CCD video camera (XC-77, Sony Corporation, New York, NY). The video signal was digitized by a frame-grabber (PCVISION*plus*, Imaging Technology Incorporated, Woburn, MA) that was installed in one of the expansion slots of a computer (PC/AT, IBM Corporation, Boca Raton, FL). The digitized image was displayed on an RGB video monitor (PVM 1271Q, Sony Corporation, New York, NY). Software for the image processing and analysis was written by the principal investigator (T.H.) in the C programing language.

So that the electronic components would have time to stabilize their performance, the video camera, light box, computer, and video monitor were turned on at least 30 min before image processing was started. The room lighting was subdued during the acquisition of images so that ambient light entering the camera would be minimal. Each radiograph was placed on a fluorescent light box that was masked to allow the passage of light only in the area of the radiograph. The video image of a radiograph was formed by the averaging of the brightness value of each picture element (pixel) in four image acquisitions. Frame averaging was used after preliminary investigations confirmed that averaging four frames reduced background "noise" in a subtraction image by 65%.

In order to obtain the subtraction image used for lesion detection, we aligned the images of the samples in the "before-lesion" and "after-lesion" radiographs (Heaven *et al.*, 1989) and stored them in the computer. The procedure proposed by Ruttimann *et al.* (1986b) for the correction of contrast variations between two films arising from exposure and processing differences was utilized for production of a third image (image 3). This was a copy of the after-lesion image, with a contrast that more closely matched the before-lesion image. The brightness value of each pixel in the before-lesion image was then subtracted from the brightness value of the pixel in the corresponding location of image 3, and the subtraction image was displayed on the video monitor.

We used an x-y positioner (mouse) to draw a rectangle around each area of change (lesion) in the subtraction image. The rectangle included all of the lesion and a border of normal tissue. The computer then located the borders of the lesion by identifying the pixels at the points of maximum positive and negative change along each scan line within the rectangle. These points of change were defined as the junction of lesion and normal tissue. The mean brightness value of the pixels within the lesion was calculated for the before-lesion image, after-lesion image, and the contrast-corrected image 3. Each occurrence of this mean pixel value, and the values one greater and one less than this mean, was then located on the image of the aluminum ramp. The mean distance of these pixels from the thin end of the ramp was then multiplied by the slope of the ramp so that the thickness of aluminum corresponding to the density of the tooth in the area of the lesion could be obtained.

TABLE 1
MEAN CHANGES (±S.D.) MEASURED RADIOGRAPHICALLY BY METHODS A & B

Group	N	Method A Al equiv. mm	Method B Al equiv. mm
0.525	11	0.63 ± 0.20[a]	0.42 ± 0.09[a]
0.675	9	0.59 ± 0.22[a]	0.50 ± 0.08[b]
0.675E	11	0.80 ± 0.27[b]	0.47 ± 0.12[b]

Means with the same superscript in a column did not differ significantly ($P<0.05$).

Two methods for calculation of the change between radiographs were compared. In method A, the reference ramp of aluminum on the before- and after-lesion radiographs was used; in the other method, B, only the ramp on the before-lesion radiograph was used. Through method A, we calculated the mean brightness within the area of the lesion on both the before-lesion and after-lesion images. These two brightness values were then converted into two aluminum-equivalent measurements by reference to the image of the ramp on their respective radiographs. The difference between these two aluminum-equivalent measurements was the measured change in density. In method B, the lesion brightness in the before-lesion image was converted into a thickness of aluminum, as in method A. The lesion brightness in the contrast-corrected third image was located on the image of the reference ramp in the before-lesion image and converted into a thickness of aluminum. The difference between these two aluminum-equivalent values was the change measured by method B. Each pair of films was acquired and aligned four separate times. Two measurements of each lesion by the two methods were performed each time. Thus, each lesion was measured a total of eight times by each method.

Planimetric software was used for measurement of the area of the holes directly from the samples. The samples were viewed through a dissecting microscope at 25× magnification. A video image (XC-77, Sony Corporation, New York, NY) was input to an image-analysis system (Cue-2, Olympus, Lake Success, NY). The area of the drill holes was measured twice on each side of the sample. The mean of the four measurements was calculated and used as the cross-sectional area of the hole. The mean change in density measured radiographically for each of the three groups by methods A and B was compared with the mean change measured planimetrically. The mean change planimetrically is the mean cross-sectional height of the lesion. The planimetric measurements of the areas were used for calculation of the mean cross-sectional height of the lesions by Formula 1:

$$\text{mean height} = \frac{\text{area}}{\text{diameter}} \quad (1)$$

The radiographic data of the three groups were analyzed statistically by an Analysis of Variance and, where appropriate, with Duncan's Range Test (SAS Institute, 1985). The ratio of variances test was used for comparison of the variance of the data for method A and method B by each group.

Results.

The results and statistical analysis are summarized in Table 1. Method A did not differentiate between the radiographic images of the lesions made with the 0.525-mm drill and the

TABLE 2
MEAN PLANIMETRIC AREA (±S.D.), HEIGHT (±S.D.), AND METHOD B DENSITY-CHANGE MEASUREMENTS BY SAMPLE GROUP

Group	Area mm^2	Height mm	Density Changes Al equiv. mm
0.525	0.25 ± 0.02	0.44 ± 0.02	0.42 ± 0.09
0.675	0.37 ± 0.03	0.54 ± 0.02	0.50 ± 0.08
0.675E	0.39 ± 0.01	0.55 ± 0.01	0.47 ± 0.12

TABLE 3
METHOD B RADIOGRAPHIC MEASUREMENTS EXPRESSED IN MEAN (±S.D.) ALUMINUM-EQUIVALENT MM BY SAMPLE GROUP

Group	Loss Al equiv. mm	Thickness at Lesion Al equiv. mm	% Loss in Thickness
0.525	0.42 ± 0.09	8.74 ± 0.86	4.8
0.675	0.50 ± 0.08	9.29 ± 1.23	5.4
0.675E	0.47 ± 0.12	8.74 ± 0.86	5.4

images of lesions made with the larger, 0.675-mm drill. It did detect a significant difference between the two groups of lesions made with the 0.675-mm drill. Method B differentiated the 0.525-group lesions from those in the 0.675 and 0.675E groups, but it did not detect any difference between the lesions in the 0.675 and 0.675E groups. The measurement variance was significantly larger ($p<0.01$) with method A than with method B for the three groups.

The planimetric area measurement data, mean height calculations by Formula 1, and the corresponding radiographic method B measurements for each group are summarized in Table 2.

The presence of a lesion can also be reported as a percentage of loss of aluminum. Table 3 presents the mean sample thicknesses, *i.e.*, bucco-lingual thickness expressed as millimeters of aluminum, at the 11 lesion sites in the 0.525 and 0.675E groups and the nine lesion sites in the 0.675 group, as measured by method B on the before-lesion images. The right-hand column reports the percentage of change relative to original thickness.

Discussion.

In this experiment, the subtraction images only served to locate the lesions. Calculation of the mean brightness of the lesion and conversion into aluminum-equivalent thickness measurements was done on the images of the radiographs in both methods A and B. Method B was superior to method A in three important respects. First, the analyses of the data derived by use of method B differentiated between sample groups in accordance with the actual hole sizes; those derived by use of method A did not. Method A incorrectly determined the mean hole size for the 0.675 group to be slightly smaller than that of the 0.525 group. Second, method B was significantly more precise than method A, as determined by the ratio of variances test. And third, method B was more accurate. The radiographic measurements of change in density made by use of method B (Table 2) were in close agreement, within one standard deviation, with the planimetric measurements, while those derived by use of method A were not. This agreement for each of the three sample groups between the mean planimetric height measured in mm of dentin and the mean change measured radiographically in mm of aluminum is consistent with the findings of Hodge *et al.* (1935).

Two limits of resolution associated with a frame-grabber image are the number of data bits *per* pixel (dynamic range) and the number of pixels *per* image (spatial resolution). Using similar equipment, Vos *et al.* (1986) calculated a theoretical limit of resolution of 0.10-mm aluminum-equivalent. Given the eight-bit dynamic range of the frame grabber used in the present investigation, the resolution of the image of the aluminum ramp was calculated in units of mm of aluminum *per* brightness value. For this investigation, this number, 0.07-mm aluminum/brightness value, was estimated by calculation of the mean number of mm *per* brightness value over the range of brightness values at the 20 lesion sites. One brightness value is the smallest measurable change; therefore, 0.07-mm aluminum-equivalent is the dynamic range limitation for this experiment. This resolution can be improved by use of a frame grabber that digitizes and stores more than eight bits of data *per* pixel.

The spatial limitation of resolution associated with the frame-grabber image of the aluminum ramp is the number of mm each pixel represents. For this investigation, the resolution was 0.05 mm/pixel. Multiplication of this number by the slope of the ramp (0.623) yields the minimum change in thickness of 0.03 mm aluminum/pixel measurable with this system. This resolution can be improved if the optical magnification of the image is increased or if a frame grabber with more pixels *per* image is used. The limitations of dynamic range and spatial resolution are cumulative and yield an effective limit of resolution of 0.10 mm of aluminum for this experiment, which is in agreement with Vos *et al.* (1986).

For confirmation of this, an analysis was attempted on four of the samples, which contained 11 lesions, and which had been radiographed three times: once before lesions were created, again after 0.525 holes were drilled, and a third time after the 0.525 holes had been enlarged with the 0.675 drill. After subtraction of the image with the lesions made with the 0.525 drill from the image of the same sample when it contained the lesions made with the 0.675 drill, it was not possible for us to locate an area of change in the subtraction image. The difference between the means of these two groups is 0.05 aluminum-equivalent mm, approximately one brightness value, and below the theoretical limit of resolution of the equipment. When the operator used the mouse to place a rectangular outline around the area thought to contain the lesion, the lesion detection software was unsuccessful in finding the lesion.

So that the reasons method B produced better results than method A could be examined, the image of the ramp that was on each radiograph was divided in half along its length, and the mean brightness of each half was calculated. These values were compared between the before-lesion and after-lesion images for the 12 film pairs in this experiment. For nine of these pairs, the after-lesion radiograph was brighter than the before-lesion radiograph. For all nine of these, the radiographic change as measured by method A was greater than the change measured by method B. In two of the three pairs where the before-lesion radiograph was brighter than the after-lesion radiograph, the change measured by method A was less than the change measured by method B. Thus, a pattern of larger measured differences when the after-lesion radiograph was brighter and of smaller differences when the after-lesion radiograph was darker was present in 11 of the 12 pairs of radiographs. Also, in these 11 film pairs, the difference between the method A and method B measurements increased as the difference in brightness between the films increased. Therefore, the larger method A means for the three sample groups can be attributed to the nine film pairs with brighter after-lesion radiographs and larger method-A-measured differences. The greater standard deviation exhibited by method A is probably the result of the additional error introduced when two ramp images, as opposed to the one ramp image used in method B, were located.

Other investigators have used techniques similar to those in the present experiment to make quantitative measurements based on changes in radiographic density. Ruttimann *et al.* (1986a) used the image of one ramp for their measurements, and Vos *et al.* (1986) used two images of the ramp. In the present investigation, the single-ramp technique was more precise, as measured by the standard deviation of the measurements. Method B used the lesion brightness values from the before-lesion image and the contrast-corrected image and converted them into two aluminum-equivalent thicknesses by reference to the image of the ramp on the before-lesion image. The difference between these thickness measurements was the change. In contrast, Ruttimann *et al.* (1986a) used the subtraction image produced between the before-lesion radiograph and the contrast-corrected after-lesion radiograph for lesion brightness calculation and conversion to cortical bone equivalent thickness change. When the amount of change is measured on the subtraction image, as by Ruttimann *et al.* (1986a), there is a need to match the x-ray beam attenuation at the ramp to the attenuation at the lesion (Webber *et al.*, 1989). The accuracy of the technique proposed by Ruttimann *et al.* (1986a) will probably not be as good as method B, due to the potential error introduced by the attenuation at the ramp being matched to that at the lesion, and the need for contrast-correction of both the area of the lesion and the area that overlies the ramp in the after-lesion radiograph. The technique of Vos *et al.* (1986) is similar to method A. They differ mainly by the use of corrections for "systematic" and "random inhomogeneities" by Vos *et al.* (1986) and the order of the steps taken in the quantification process. Even with the corrections for inhomogeneities, the technique of Vos *et al.* (1986) appears to be subject to the same inaccuracies as method A, which increase as the difference in brightness between the before-lesion and after-lesion radiographs increases.

Studies that measured the extent of lesion penetration toward the pulp on bitewing radiographs have shown this to be an insensitive index, as compared with direct clinical or histological examination (Marthaler and Germann, 1970; Gwinnett, 1971; Mejàre *et al.*, 1985). Similarly, studies of the initiation and progression of approximal caries lesions have concluded that lesion progression could not be accurately determined from a bitewing radiograph alone and needed to be evaluated in the context of a patient's caries activity status (Espelid, 1986; Shwartz *et al.*, 1987; Pitts, 1983).

The present investigation has shown that the initial detection of a lesion by method B lies in the 0.05-0.42-mm range. Once a lesion has been detected, method B can differentiate between two groups of lesions differing in density by 0.05 mm of aluminum, or 0.6% (Table 3). Radiographic method B can provide lesion-density data that may be useful by themselves or in combination with penetration or area measurements for provision of a three-dimensional estimate of lesion size. These nondestructive measurements are applicable to the *in vitro* study of artificial caries lesions, and, with the control of film-exposure geometry, they may produce better *in vivo* diagnostic criteria for the longitudinal evaluation of preventive measures and restorative decisions.

REFERENCES

AMERICAN DENTAL ASSOCIATION (1979a): **1979 Survey of Dental Services Rendered**, Bureau of Economic and Behavioral Research, Chicago: ADA, pp. 1–2.

AMERICAN DENTAL ASSOCIATION (1979b): Dental Fees Charged by General Practitioners and Selected Specialists in the United States, *J Am Dent Assoc* 102:675–679.

ESPELID, I. (1986): Radiographic Diagnoses and Treatment Decisions on Approximal Caries, *Community Dent Oral Epidemiol* 14:265–270.

GRÖNDAHL, H.-G.; GRÖNDAHL, K.; and WEBBER, R.L. (1983): A Digital Subtraction Technique for Dental Radiography, *Oral Surg Oral Med Oral Pathol* 55:96–102.

GWINNETT, A.J. (1971): A Comparison of Proximal Carious Lesions as Seen by Clinical Radiography, Contact Microradiography, and Light Microscopy, *J Am Dent Assoc* 83:1078–1080.

HEAVEN, T.J.; COGEN, R.B.; and FIRESTONE, A.R. (1989): A Comparison of Two Registration Methods for Digital Subtraction Radiography, *J Dent Res* 68:253, Abst. No. 571.

HODGE, H.C.; BALE, W.F.; WARREN, S.L.; and VAN HUYSEN, G. (1935): Factors Influencing the Quantitative Measurement of the Roentgen-ray Absorption of Tooth Slabs, *Am J Roentgenol* 34:817–838.

MARTHALER, T.M. and GERMANN, M. (1970): Radiographic and Visual Appearance of Small Smooth Surface Caries Lesions Studied on Extracted Teeth, *Caries Res* 4:224–242.

MEJÀRE, I.; GRÖNDAHL, H.-G.; CARLSTEDT, K.; GREVER, A.-C.; and OTTOSSON, E. (1985): Accuracy at Radiography and Probing for the Diagnosis of Proximal Caries, *Scand J Dent Res* 93:178–184.

MUHLER, J.C.; SPEAR, L.B.; BIXLER, D.; and STOOKEY, G.K. (1967): The Arrestment of Incipient Dental Caries in Adults After the Use of Three Different Forms of SnF_2 Therapy: Results After 30 Months, *J Am Dent Assoc* 75:1402–1406.

PITTS, N.B. (1983): Monitoring of Caries Progression in Permanent and Primary Posterior Approximal Enamel by Bitewing Radiography, *Community Dent Oral Epidemiol* 11:228–235.

PITTS, N.B. (1984): Detection and Measurement of Approximal Radiolucencies by Computer-aided Image Analysis, *Oral Surg Oral Med Oral Pathol* 58:358–366.

REKOLA, M. (1987): Approximal Caries Development During 2-Year Total Substitution of Dietary Sucrose with Xylitol, *Caries Res* 21:87–94.

RUTTIMANN, U.E.; WEBBER, R.L.; and SAFFER, A. (1986a): Calibrated Volume Determination of Localized Bone Lesions by Subtraction Radiography: In: **Medinfo 86**, R. Salamon, B. Blum, and M. Jørgensen, Eds., Amsterdam: Elsevier, pp. 634–637.

RUTTIMANN, U.E.; WEBBER, R.L.; and SCHMIDT, E. (1986b): A Robust Digital Method for Film Contrast Correction in Subtraction Radiography, *J Periodont Res* 21:486–495.

SAS Institute, Inc. (1985): The GLM Procedure. In: **SAS User's Guide: Statistics, Version 5 Edition**, Cary, NC: SAS Institute, Inc., pp. 433–506.

SHEPHERD, P.R. (1945): The Estimation of the Rate of Spread of Dental Caries, *Br Dent J* 78:73–75.

SHWARTZ, M.; PLISKIN, J.S.; GRÖNDAHL, H.-G.; and BOFFA, J. (1987): *Benefits of Alternative Schedules for Bitewing Radiographs*, NCHSR Research Summary Series, DHHS Publication No. (PHS) 87-3407.

VOS, M.H.; JANSSEN, P.T.; VAN AKEN, J.; and HEETHAAR, R.M. (1986): Quantitative Measurement of Periodontal Bone Changes by Digital Subtraction, *J Periodont Res* 21:583–591.

WEBBER, R.L.; TZUKERT, A.; and RUTTIMANN, U. (1989): The Effects of Beam Hardening on Digital Subtraction Radiography, *J Periodont Res* 24:53–58.