Measurement of fine structures in roentgenograms

I. A microdensitometric method

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A microdensitometer incorporating a rebuilt light microscope is described. In this apparatus, light from a stabilized source passes through a film and impinges on a photomultiplier attached to the microscope. The voltage generated by the light is read on a digital multimeter. The coefficient of variation of the densitometric measurements in the range of measurement of interest for analysis of dental roentgenograms was less than 3 %. The conversion of pairs of voltage measurements to aluminium equivalents, which reflect differences in substance in the object, and to »optical density units» (ODU), which express differences in image contrast, is described.

Roentgenograms of simulated tooth roots, parallel ivory cones with central canals, were analyzed in the densitometer. The breadth of the image of the canal in the plane of the film was measured as was the photographic density of the image of the canal which was used to estimate the depth of the canal and the contrast between its image and that of the surrounding dentine. The precision of the methods of measurement of the breadth was 0.13 mm, and of the differences in substance and contrast, 0.05 mm Al and 0.03 ODU, respectively.

Key-words: Densitometry, X-ray; radiography; endodontics

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A common problem in diagnostic roentgenology is the registration in the roentgenographic image of fine structures, especially those with small differences in radiolucency. In dental roentgenology, such fine structures may be normal anatomical features such as the root canals of teeth or changes indicative of pathology such as carious lesions. The detection of such details is dependent upon the extent of the object in the film plane as well as its contrast, its radiolucency relative to that of surrounding tissues. The differences in radiolucency provide information regarding both the thickness and density of that part of the object relative to those of the surrounding tissue. Two important questions often arise in this connection: what is the smallest difference in substance which can be detected by the roentgenographic system and how do the different exposure parameters affect this detection limit?

There have been a number of attempts to determine the optimal conditions of exposure for distinguishing fine structures as judged by the subjective evaluation of the roentgenographic images in double-blind studies. *Webber, Benton & Ryge* (1968) had eleven observers register caries

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on dental roentgenograms obtained at various exposure parameters. The film which gave the least number of diagnostic errors was judged to be best. Similarly, *Manson-Hing* (1971) had ten dentists record fractures in the lamina dura of the root of a tooth in order to determine the smallest fracture which is visible to the naked eye in roentgenograms.

By measuring the degree of blackening of the film a measure of the relative radiolucency of different parts of the object can be objectively obtained. With the aid of a densitometer and a technique for making periodically identical projections, *Björn, Henrikson & Omnell* (1951) measured the amount of periapical bone. The method involved the use of an aluminium step-wedge, a so-called penetrometer, projected on the same film as the part of the jaw being examined. The radiolucency of the bone could be compared with that of the penetrometer and the amount of bone expressed in aluminium equivalents. Using a similar method *Lundberg* (1955) registered new bone formation in the alveolar process following tooth extraction. A quantitative analysis of bone salt *in vivo* by means of a roentgenologic, photometric method was described by *Omnell* (1957).

Lindström & Philipson (1969) described a microdensitometer intended for use in microradiography. The apparatus consisted of a combination of a highly sensitive microscopic photometer and an integrating digital voltmeter with a paper tape punch. The precision of this instrument expressed as the coefficient of variation varied from 0.3—1.1 %.

The aim of the present investigation was to develop and evaluate a densitometric method for measuring the dimensions in the film plane and the contrast of the images of fine structures on dental roentgenograms. The method was intended for use in studying the effects of changes in exposure parameters on the above mentioned variables (*Hedin*, 1974).

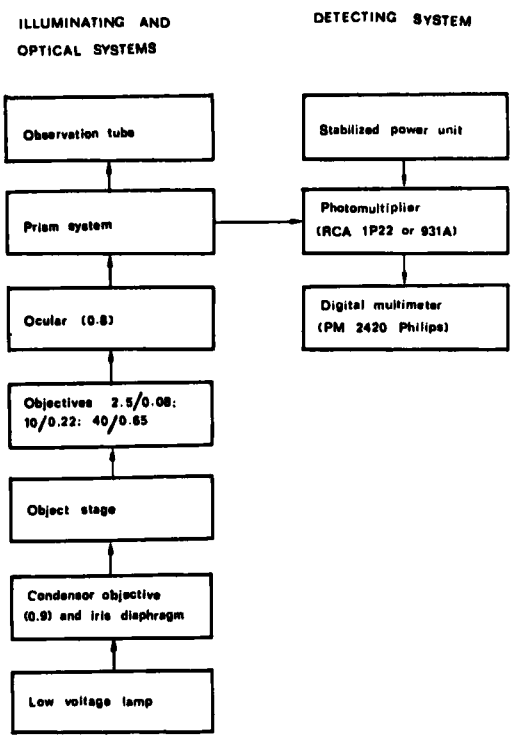

Fig. 1. Block diagram showing the construction of the densitometer system (after *Lindström & Philipson*, 1969).

MATERIAL AND METHODS

Densitometric equipment

The densitometer described below, based on a modification of those described by *Lundberg* (1955) and *Bertoft, Kristenson & Persson* (1961), fulfills the requirements of a relatively small measurement area and a highly sensitive detector system. The components of the densitometer are shown in Fig. 1. A light microscope (Zeiss standard junior) was equipped with a portable densitometer described by *Engström, Wegstedt & Welin* (1948). Through

an extra ocular it was possible to observe the part of the object under investigation. The light source was a low voltage lamp. The input voltage to the transformer for the lamp, 4.5 or 5.5 V, was stabilized with an average deviation of 1 %. Before reaching the film, the light was collimated by an iris and a condenser lens. The area of film illuminated was approximately 1 mm in diameter. On the object table was mounted a rebuilt slide holder in which the roentgenogram was placed. With the aid of a micrometer screw, the holder could be moved left-right and its displacement could be recorded with precision. The objective used was designated 40/0.65; the ocular gave 8 × magnification. Using this objective the area of the film »seen» by the densitometer was approximately 0.2 mm in diameter. Light passing through the microscope was refracted by a system of prisms so that it fell, in part, on the cathode of the photomultiplier tube and, in part, on the observation eyepiece. By focusing before each reading, the distance between the object and the objective, and thus the area of the spot being examined, was kept constant. The photomultiplier was provided with a high voltage supply with which it was possible to alter the potential over the dynodes and thereby regulate the amplification. The voltage drop created at the photomultiplier anode was registered on a Digital multimeter (PM 2420, Philips) with an accuracy of ± 0.5 % of full scale and a reproducibility of 1 scale unit. The potential was measured with the scale 100 mV or 1000 mV in circuit; the input resistance was 1 MΩ in both cases. The measured voltage could be read directly as a combination of numerals which changed at intervals of slightly less than one second.

Test objects

In order to estimate the precision of measurements made with this densitometer, roentgenograms of test objects of dentine with small cylindrical holes (canals) producing small differences in film density were analyzed. The test objects, which were to be used in later experiments as well, were constructed as follows: Dentine from elephant (ivory) was cut into pieces 10 × 10 × 30 mm which were turned in a lathe to form right circular cones. The greatest diameter was approximately 9.0 mm and the smallest diameter 1.5 mm. Each cone was cut parallel with its base to form 5—6 plane parallel truncated cones, each 3—4 mm high. Using precision drills 1.0, 0.7, 0.5 or 0.3 mm in diameter, central canals were created in all pieces. When the pieces were reassembled, they thus formed four cones, each containing a central canal but with different canal diameters. Measurements on the plane parallel sides of the cones showed that the diameters of the canals exceeded the dimensions of the drills by 0.02—0.04 mm.

To the long cone of a Philips Practix 90/20 roentgen unit a film holder was fixed at a distance of 345 mm from the focus and perpendicular to the central ray, which passed through the center of the film holder. The electronic timer of this unit was checked by counting the pulsations of the emitted rays and was found to be accurate. The total filtration of the unit was the equivalent of 2 mm aluminium. The film used was Kodak Ultra Speed. All exposures were made with an approximately 2 mm thick lead sheet behind the film.

In making the film exposures, each of the truncated cones was placed as close to the film as possible with its central canal

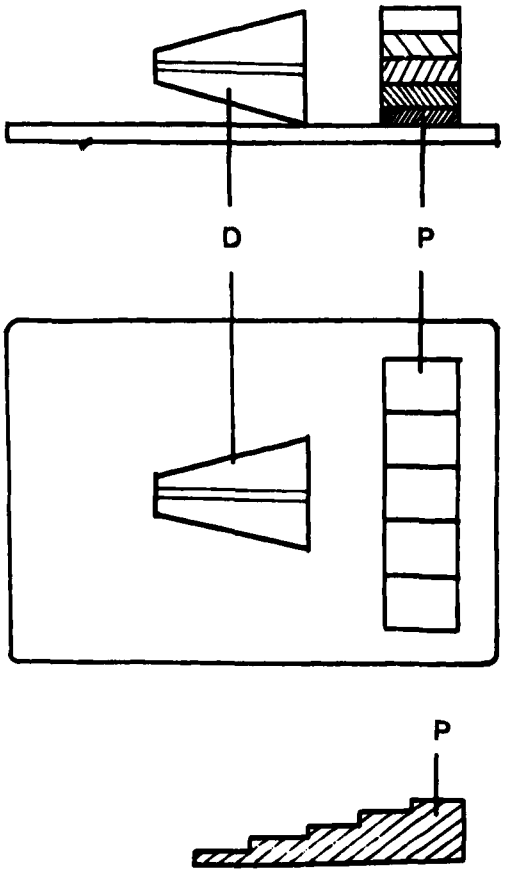

Fig. 2. Dental film with dentine test object and penetrometer in place, viewed from the side (upper diagram) and from above (center diagram). A longitudinal cross-section of the penetrometer is shown below. P = penetrometer, D = dentine.

parallel to the film and was fixed in position with wax. On each film an aluminium step-wedge, a so-called penetrometer, in which the steps were 0.5 or 1.5 mm, was exposed simultaneously with the test object (Fig. 2). The height of the penetrometer could be increased by a supplementary block. The thickness range of the penetrometer was such that all film densities present in the image of the dentine object were included in the range of film densities in the image of the penetrometer. The diameter of the canal in the object and the exposure time used were projected on each film using lead numerals. Double films were used but only the film nearest the object was developed. Exposure times were chosen so as to obtain films in which the object was subjectively judged to be either under, »optimally» or over-exposed. All films were developed immediately in an automatic developing machine (Procomat junior, Elema-Schönander).

In the densitometric analysis of a film, the film was placed in the film holder and microscope stage was rotated until the image of the canal was perpendicular to the direction of scanning (left-right). Before each reading, both film emulsion layers, which appeared as one through the observation eyepiece, were brought into focus. The film was scanned by advancing the micrometer screw and taking a densitometric reading every 0.1 mm. Before and after each scan densitometric readings were taken of the images of the different steps of the aluminium penetrometer. When the values obtained were plotted with the densitometer readings (mV) on the ordinate and the distances across the image on the abscissa, the result was a superiorly convex curve with a central concavity (Fig. 3). The concavity corresponded to the image of the drilled

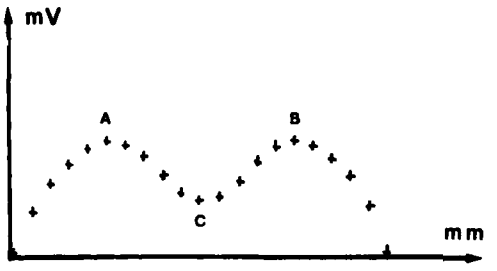

Fig. 3. Graphic representation of the photometer readings (ordinate) as the beam of light passes the image of a dentine test object. A and B represent the densitometric limits of the outer dimensions of the canal. C is the point in the image of the drilled canal with the highest photographic density.

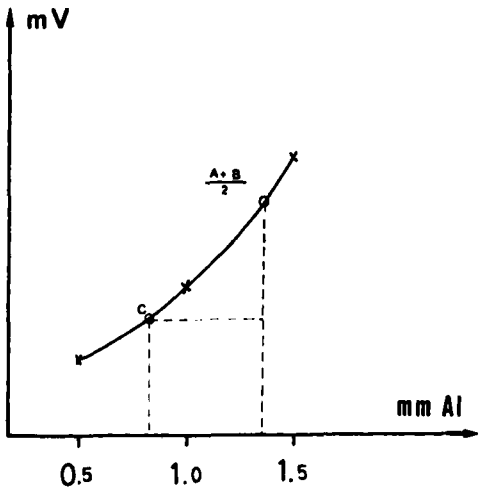

Fig. 4. The densitometer readings from the image of the penetrometer with points read from the image of an object superimposed. The substance difference, expressed in metal equivalents, can be read from the abscissa.

canal, the breadth of which in the plane of the film was assumed to be the difference on the abscissa between the two maxima A and B. The measured voltage maximum the average of A and B) and the minimum (C) representing the canal were used to obtain a measure of the depth of the canal perpendicular to the film plane in aluminium equivalents and the contrast of the image of the canal to that of the surrounding dentine.

In order to obtain a measure of the canal depth, the maximal difference in substance between the canal and the surrounding dentine, the image of the aluminium penetrometer was used as a reference and the analysis performed as follows: For each exposure, a curve was plotted with the densitometer readings corresponding to the steps of the penetrometer on the ordinate and the thickness of the penetrometer on the abscissa (Fig. 4). With the aid of this curve, the minimum and maximum values for the image of the canal could be converted to aluminium equivalents. In this way, the value for the light transmission of the image obtained in mV were converted to a difference in substance in mm Al. In addition to making it possible to obtain a measure of the substance difference, the use of the penetrometer also served to achieve independence of differences in the film and the conditions of exposure or development.

The measure of a difference in substance, expressed in aluminium equivalents, cannot be used to compare the effects of different tube potentials and/or exposure times on the contrast of the image. In order to study how the image contrast between the canal and the surrounding dentine walls of the object varied with these parameters of exposure, the measured voltage maximum and minimum must be converted to units of difference in optical density. This was done in the following manner: A photographic control scale for transmitted light containing 14 fields of different densities (Kodak Control Scale T-14) was measured in the densitometer. The difference in photographic density between two adjacent fields was defined as 1 ODU (optical density unit) for the purposes of this investigation. The difference in photographic density according to the manufacturer was 0.15. When the voltages measured for the control scale were converted to their logarithms and plotted, a straight line was obtained; *i.e.* the logarithm of the voltage measured was directly proportional to the film density (Fig. 5). According to the definition of photographic density, the difference in film density between two adjacent steps on the control scale, is

$$\triangle \mathrm{ODU} = -\frac{1}{0.15} \log \left(\frac{I_1}{I_2}\right) = K \cdot \log \left(\frac{mV_1}{mV_2}\right)$$

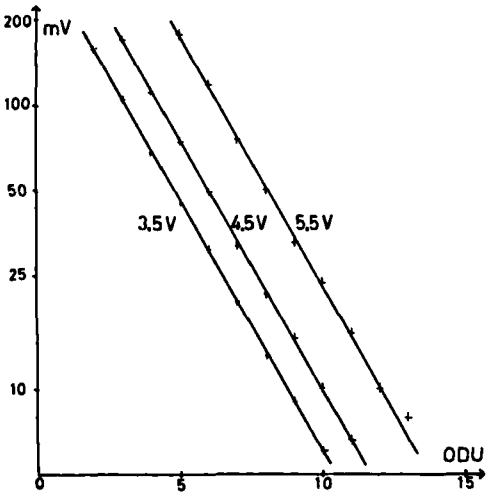

Fig. 5. Graphic evaluation of the relationship between light passing through the photomultiplier and through a photographic control scale at three different microscope lamp voltages.

where I_1 and I_2 are two values for transmitted light which gave rise to voltages mV_1 and mV_2. In 10 such plots the average K was $-\frac{1}{0.17} = -5.88$ with a standard deviation of 0.16.

FINDINGS

Densitometric measurements

The precision of the densitometer was influenced chiefly by variations in the intensity of the light source and by variations in the response of the detector system. When the density of the same area of a film (Kodak Ultra Speed) was measured 30 times, the precision was 0.0002 ODU or 0.02 %. To determine whether the precision varied for different film densities, readings were taken of eight fields of different densities, *i.e.* images of the steps of the aluminium penetrometer. Four of the fields were read with the 1000 mV scale in circuit and four with the 100 mV scale. The apparatus was allowed to warm up for 30 minutes before the readings were taken. Each field was measured 30 times during a period of 20 minutes, with removal and replacement of the film between readings. The results are shown in Table I, which also gives the coefficient of variation in percent. The variation of the densitometer readings for four different fields with time are shown graphically in Fig. 6. The values decreased with time, the relative decrease (%) being approximately the same for all four fields.

Table I. *The precision of the densitometer in the measurement of 8 fields of different film densities. 30 measurements of each field were carried out without moving the film with scales 100 and 1000 mV in circuit during a 20 minute period*

Scale mV	Mean mV	Precision (S.D.$_k$) mV	Coefficient of variation %
100	3.3	0.07	2.1.
100	11.7	0.19	1.6
100	36.4	0.45	1.2
100	67.2	0.73	1.1
1000	41	1.0	2.4
1000	112	1.8	1.6
1000	281	5.6	2.0
1000	449	14.6	3.1

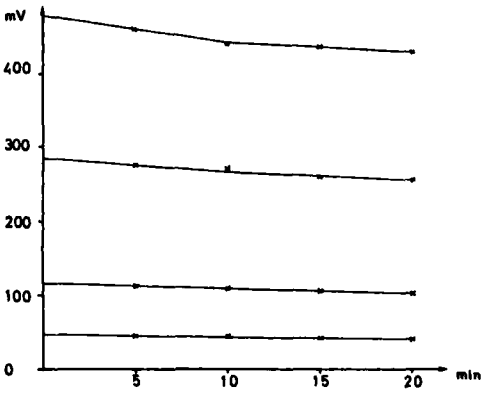

Fig. 6. Densitometer reading in mV read for four fields with different photographic densities during a period of 20 minutes.

Measurements of image dimensions in the film plane

The density measurements were made on roentgenograms as the beam of light scanned across the image of the drilled canal perpendicular to the direction of the canal and the width of the canal was taken from the distance between maxima, as described above. An error in the positioning of the film of 5° from the perpendicular would result in only a 0.4 % increase in the estimate of the width of the canal. The accuracy and precision of the advancement of the film on the object table were not determined. However, these errors can be assumed to be so small as to not contribute significantly to the total error.

A study was made of 30 images of parallel truncated cones chosen at random and representing cones with different outer dimensions and canal diameters. The films differed in average film density. On each film the diameter of the image of the canal was measured on each of two different occasions and the error in the method (S.D.k) was calculated from the differences between pairs of measurements (Table II). The error is approximately equal to the 0.1 mm advancement of the micrometer screw between measurements.

Table II. *The precisions of the methods of measurement of the breadth in the film plane and the differences in substance and contrast of the images of canals in objects of dentine. The objects had outer cone diameters of 2—8 mm and the canal diameters were 0.3—1.0 mm*

	N	Range	$S.D._k$
Breadths	30	0.4 —1.6 mm	0.13 mm
Substance differences	30	0.07—0.66 mm Al	0.05 mm Al
Contrast differences	30	0.11—0.85 ODU	0.03 ODU

Measurement of object dimensions perpendicular to the film plane and image contrast

Using the method described above (Fig. 4) the maximum difference in substance between the canal and the dentine walls was calculated from measurements on the 30 randomly chosen films on two separate occasions and expressed in aluminium equivalents. The maximum difference in film density in the scan across the image of the canal in the 30 films was also calculated on two separate occasion and expressed in optical density units (ODU). The errors in the methods (S.D.) were calculated from the differences in the measurements on the two occasions and the results are presented in Table II.

DISCUSSION

In the densitometric analysis of small objects, *Lindström & Philipson* (1969) stated that the film used must be fine-grained and that the field of measurement must be small and possible to localize exactly. In the present study, a highly sensitive film commonly used in dental practice was purposely chosen. Although its geometric resolving capacity may be poorer than that of other films, the size of the field of measurement, 0.2 mm in diameter, was such that grain size should not be of any importance. *Henrikson* (1963) has shown that the contrast properties of the film used (Kodak Ultra Speed) do not differ from those of other dental films.

In the present study the precision of the densitometer and the method of measurement in densitometric analysis of roentgenograms was systematically investigated. Repeated measurements of the density of a given area of film without moving the film showed very good precision. When a

number of fields of different film density were measured over a period of 20 minutes, sources of error associated with variations in the film emulsion, the homogeneity of the aluminium penetrometer, the accuracy of replacing the film and the drift of the densitometer affected the results. A densitometer of the type used has a warm-up time of at least 20 minutes. Even after this time, the absolute readings were unstable for at least a further 20 minutes. This can be explained by differences in the temperature coefficients of the resistances and condensers in the voltage divider of the photomultiplier tube. However, the total coefficient of variation was approximately 2 %, which must be regarded as a satisfactory value. As the total time for the analysis of a single film was 2—3 minutes at the most, the effect of this drift should be very small and the coefficient of variation, in fact, even smaller than 2 %.

That the measured constant in the calculation of ODU did not agree with the theoretical value, *i.e.* that the slopes of the curves in Fig. 5 are not identical with the theoretical, could either be due to an error in the photographic control scale or, more probably, to higher light values producing proportionately higher amplification in the photomultiplier tube and thereby generating a higher voltage. The constant calculated for the densitometer system was used in this study.

The diffusion of light in the film and the possible effects of such diffusion were not studied. *Lindström & Philipson* (1969) studied the effects of the size of the illuminated field and of the amount of background illumination of the results. The errors introduced were insignificant, and the same can be assumed to apply to the densitometer used in the present study. Furthermore, this source of error in the method would have decreased the slopes of the curves in Fig. 5. Any possible effect in this direction was completely outweighed by the previously-mentioned effect which increased the slope.

As a part of the study of methodological error, a measure of the depths of the canals was obtained by comparison of their images with those of the steps in a penetrometer and, for the same images, measurements of differences in film density (in ODU) were carried out. As the standard deviations in both types of determination were very low, the precision of the densitometric equipment described was judged adequate for the measurement of small differences in substance of dentine as seen roentgenographically. The accuracy of the method for determining substance differences is discussed in a subsequent article (*Hedin*, 1974).

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