Measurement of fine structures in roentgenograms

II. Studies on canals in dentine models

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This study deals with the objective experimental recording of the roentgenographic reproduction of narrow canals in dentine objects of various sizes, intended to simulate the root canals of teeth. A common dental film was used and the roentgen tube voltages were in the range usual in dental practice. A bone phantom was constructed to simulate clinical conditions. Densitometric measurements of canal breadth in the plane of the film with the apparatus and method used were higher than the true values. The error became greater as the thickness of the dentine object increased. Varying the voltage between 50, 60 and 90 kV had little effect on the results. Over- or underexposure of the films did not improve the accuracy of breadth measurement of the canals with the recording method used. The differences in densitometer reading between the canal and the dentine walls were expressed in metal equivalents with the aid of an aluminium penetrometer exposed and reproduced simultaneously with the object. This gave a measure of the difference in substance of the object. The same densitometer reading could also be used to measure the image contrast of the canal on the film. This was expressed in »optical density units» (ODU), making it possible to compare different tube voltages and degrees of blackening. The broadest canals in narrow objects were less well reproduced. The tube voltage had little effect on the results but in most cases, as expected, the highest tube voltage (90 kV) gave the poorest contrast. The average film density was important in determining the contrast between the image of the drilled canal and the dentine walls.

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

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In the diagnosis and therapy of endodontic disease, one is frequently confronted with the question of the number and anatomy of the root canals. This can often be determined by roentgenologic examination. A number of authors have emphasized the importance of adequate roentgenography (*Muratori*, 1967; *Friend* 1969), which provides the only means of clinically detecting ancillary root canals.

The endodontic literature contains no description of the optimal physical conditions for reproducing fine structures of this type, although many authors have stressed the value of using several projections (*Ingle*, 1965; *Mumford*, 1966; *Nicholls*, 1967; *Grossman*, 1970).

A theoretical explanation of how radiographic contrast is created on a roentgenogram is to be found in textbooks of oral roentgenology. Different degrees of contrast can be obtained, depending on

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which part of the characteristic curve of the film is used. With direct exposure films, the radiographic contrast will increase when the relative exposure increases up to a certain limit (*Omnell*, 1971). Fairly large differences in exposure are required to produce subjectively visible differences in the photographic density. In images that are too light or too dark it is said to be difficult to distinguish differences in density with the naked eye (*Wuehrmann & Manson-Hing*, 1969; *Stafne*, 1969; *Bhaskar*, 1970; *Møller-Jensen*, 1971; *Omnell*, 1971).

Lysell, Mårtensson & Omnell (1968) and others have explored the theoretical relationship between a difference in thickness in a roentgenographed object and the corresponding difference in the roentgenographic density. By means of a formula which they developed, they demonstrate that for a given difference in thickness, the corresponding difference in photographic density increases with increasing gamma values and with decreasing energy. This work has been experimentally confirmed by *Hollender & Lysell* (1972) with the aid of a roentgen diffraction apparatus.

Using a phantom model, *Webber & Ryge* (1969) investigated the changes in the roentgenographic image of enamel and soft tissue when different voltages and accessory filters were used. The characteristic film curves constructed were largely the same for all combinations of voltage and filter and for both enamel and soft tissue. The tube voltage was varied from 65 kV to 90 kV and the aluminium filtration from 2.5 to 8.5 mm. On the basis of these results, the authors concluded that there was little difference in the diagnostic information (contrast) in films exposed with different voltages and/or different filters and that the voltage giving the lowest dose was that for which only a few per cent penetrated the object.

There have been a few studies of how small differences in subject contrast corresponding to proximal sites of caries lesion can best be demonstrated roentgenographically. *Webber, Benton & Ryge* (1968), using a number of observers in a double-blind study on skull preparations, concluded that films taken with a tube voltage of 90 kV give rise to more diagnostic errors than those taken at 65 kV.

Manson-Hing (1971) had ten dentists register a fracture in the lamina dura of a tooth on films taken at different tube voltages. The best results were obtained with films made in the 60 to 75 kV range, probably, according to the author, because dentists are most accustomed to films taken under these conditions.

There has been no study of how root canals on different sizes can best be demonstrated roentgenographically. The purpose of this investigation, therefore, was to attempt to clarify in a phantom study how the image of a root canal varies in breadth and blackness with variations in the lumen of the canal, the thickness of the root and certain parameters of exposure, and, if possible, to define the optimal conditions for demonstrating a root canal in a roentgenogram.

MATERIAL AND METHODS

The radiation source used was Philips Practix 90/20 with electronic timer. The total filtration was 2 mm Al. A film holder mounted on the tank-unit of the apparatus gave a constant focus-film distance of 345 mm. The film was Kodak Ultra Speed. All films were developed immediately in a Procomat Junior developer (Elema-Schönander).

The test bodies used have been described elsewhere (*Hedin, Lundberg & Wing*, 1974). They consisted of truncated parallel cones of dentine with outer diameters of 1.5 mm to 9.0 mm. Canals of various diameter (0.3; 0.5; 0.7 and 1.0 mm) were drilled in the centers of the cones.

The test bodies, *i.e.* the truncated parallel cones, were roentgenographed both free and within a bone phantom constructed to more closely simulate clinical conditions. The components of the phantom complied with the specifications of *Henrikson* (1963) regarding correspondence to organic bone tissue. Thus, the bone phantom contained »cortical bone», consisting of 45 % $Ca_3(PO_4)_2$ and $CaCO_3$ (39 and 6 parts respectively), mixed with and bonded together with 55 % polyethylene (Merck 7422). It also contained »bone marrow», consisting of 11 % calcium salts and 89 % polyethylene, and water. Polyethylene has about the same roentgen absorption as organic tissue or water. The salts and polyethylene were carefully mixed and bonded.

To determine the approximate proportions in which the components should be present in the phantom, the same region of the lower jaw was roentgenographed in five persons. An aluminium penetrometer inserted above the occlusal surface of the teeth was reproduced simultaneously. With the aid of the densitometer, a mean value for the radiolucency of the jaw at the midpoint of the length of the root could be calculated in metal equivalents, and the bone phantom was constructed so as to correspond to this mean. The phantom thus came to consist of 40 mm H_2O, 3 mm »cortical bone» and 3 mm »bone marrow» (Fig. 1).

A group of truncated parallel cones were selected in which the outer diameter of some part of the cone, measured with a sliding caliper, was 2.0; 5.0 or 8.0 mm. The outer dimensions of a real tooth root fall within this range. All four canal diameters were represented.

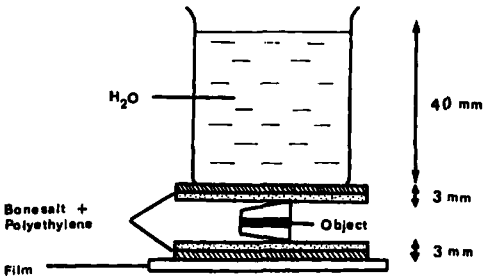

Fig. 1. The components of the phantom model in cross section. In descending order: 40 mm H_2O, 1.5 mm »cortical bone», 3.0 mm »bone marrow» and 1.5 mm »cortical bone».

A dentine cone was positioned as close to a dental film as possible, with the drilled canal parallel to the film, and fastened with wax. When the test objects were roentgenographed within the bone phantom described above, the cones were at a somewhat greater distance from the film. Without the phantom, the canals were at 1.4, 3.0 and 4.7 mm from the film for outer diameters 2.0; 5.0 and 8.0 mm respectively. Within the phantom, the canals were at 4.5, 6.0 or 8.0 mm from the film.

To evaluate the sources of error that would arise from the canals being irradiated at different distances from the film, a control was performed with the same object-to-film distance. The drilled canals were all at a distance of 4.7 mm from the plane of the film.

An aluminium step-wedge was always placed beside the cones in contact with the film, and beside the bone phantom when the latter was used. Roentgenograms were obtained using the source of radiation and the film holder described above and using a number of exposures. The tube voltages were 50 kV; 60 kV and 90 kV. For technical reasons, it was not possible to expose with an equally large focus for all

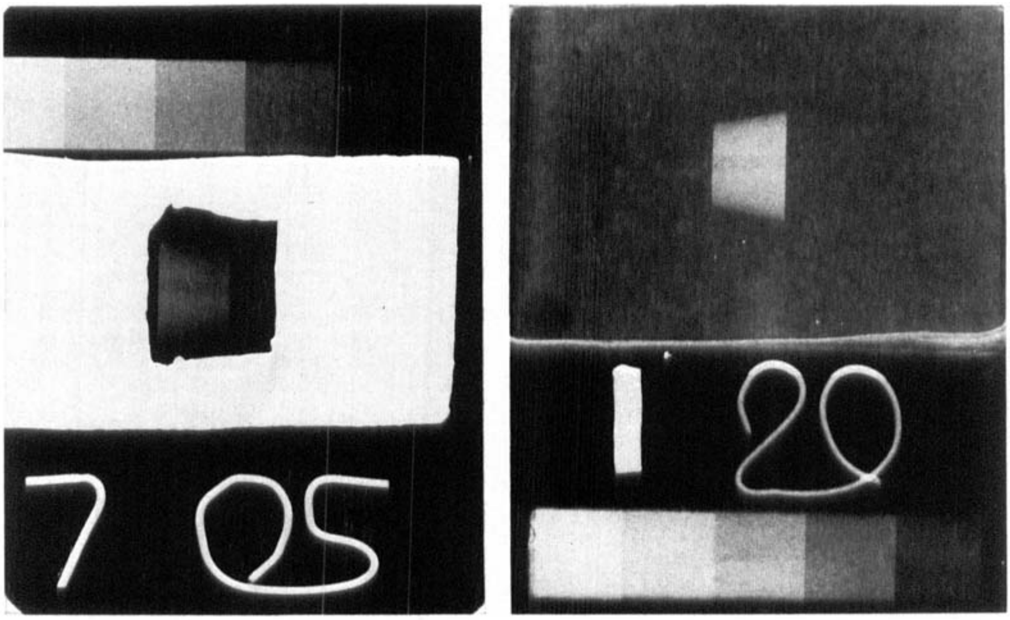

Fig. 2. Roentgenograms of dentine cones containing drilled canals, without (left) and with (right) the bone phantom. The diameter of the canal and the exposure time are indicated by lead numerals.

three tube voltages. The smaller focus was used for 50 and 60 kV and the larger focus for 90 kV. According to the manufacturer, the smaller focus should be 0.6 × 0.6 mm and the larger focus 1.8 × 1.8 mm.

The exposure time was adjusted so that a subjectively »optimal» density, a low density, and a high density film were obtained for each tube voltage. »Optimal» density in this case means that when the film was viewed in an ordinary viewing box (DVT viewing apparatus with a 22 W fluorescent lamp) there was a harmonious balance between light and dark areas and every field in the image of the aluminium penetrometer differed clearly in blackness from the adjacent steps. The image of the step-wedge was also used as a measure of the exposure of the film. The exposure time for the low density films was usually half, and that for the high density films double that for the »optimally» exposed films. Examples of roentgenograms with and without the bone phantom are shown in Fig. 2.

All exposed films were evaluated in the densitometer described by *Hedin et al.*, 1974. The beam of light was passed over the image of the stylized root canal at the level corresponding to an outer cone diameter of 2, 5 or 8 mm. When the film was advanced at intervals of 0.1 mm and the photomultiplier voltage was read simultaneously, the canals produced clear dips in the photometer curve and a direct comparison can be made between the true canal dimensions and those read densitometrically.

Two ways of interpreting the distance between the minimum and maximum values for the image of the canal have been previously described (*Hedin et al.*, 1974). One can express the difference in substance in terms of the steps of the aluminium wedge projected on the same film or one can express the difference in radiographic contrast in »optical density units», ODU. Differences in blackness must be expressed in ODU if comparisons are to be made between films that differ in film density or between films exposed with different tube voltages.

In comparing the effects of different tube voltages on image contrast, care was taken that the density of the image of the dentine nearest the canal was the same in all the films *i.e.* that they were in the same portion of the characteristic film curves. In addition, for one of the drill dimensions (0.7 mm), the image contrast between the canal and the dentine was measured in films taken at different exposure times.

RESULTS

The results of the measurements of canal breadth on the various roentgenograms of test bodies differing in outer dimensions and canal dimensions, alone and within the bone phantom are summarized in Tables I and II. The densitometric values obtained are given without correction for systematic errors of measurement. As the tables show, there was very little difference between the overexposed and underexposed films, as compared with those »optimally» exposed. The greatest differences were found for the thick objects. Figures 3 and 4 present graphic explanations of some of the data in Tables I and II

Table I. *Densitometric measurements of canal breadth on dentine test bodies differing in thickness and canal diameter*

Thickness 2 mm		50 kV			60 kV			90 kV	
drill		mAs			mAs			mAs	
diam.	2.5	5.0	10.0	0.8	2.5	5.0	0.8	1.6	2.4
0.3	0.4	0.5	0.4	0.5	0.4	0.5	0.7	0.5	0.6
0.5	0.8	0.7	0.7	0.7	0.7	0.7	0.6	0.7	0.7
0.7	0.9	1.0	0.9	0.9	0.8	0.9	0.8	0.8	0.8
1.0	1.2	1.2	1.3	1.3	1.3	1.2	1.2	1.2	1.2

Thickness 5 mm		50 kV			60 kV			90 kV	
drill		mAs			mAs			mAs	
diam.	5.0	10.0	30.0	2.5	5.0	10.0	1.6	2.4	4.0
0.3	0.6	0.7	0.7	0.8	0.6	0.7	0.8	0.6	0.8
0.5	1.1	0.8	0.8	1.0	0.9	1.0	0.9	0.8	0.9
0.7	1.0	0.9	1.1	1.1	1.2	1.0	1.2	1.1	1.1
1.0	1.7	1.4	1.5	1.4	1.5	1.5	1.5	1.4	1.4

Thickness 8 mm		50 kV			60 kV			90 kV	
drill		mAs			mAs			mAs	
diam.	5.0	10.0	20.0	2.5	5.0	10.0	1.6	2.4	4.0
0.3	0.6	0.6	0.8	0.7	0.6	0.7	0.9	0.7	0.6
0.5	1.0	0.9	0.9	1.0	0.9	1.0	0.9	0.8	0.9
0.7	1.1	1.1	1.1	1.3	1.3	1.2	1.2	1.3	1.4
1.0	1.5	1.4	1.5	1.4	1.3	1.4	1.4	1.4	1.4

Table II. *Densitometric measurements of canal breadth on the same dentine test objects as in Table I but enclosed in a bone phantom*

Thickness 2 mm		50 kV			60 kV			90 kV	
drill		mAs			mAs			mAs	
diam.	10.0	20.0	40.0	10.0	16.0	25.0	2.4	3.2	5.0
0.3	—	0.7	0.6	0.5	0.6	—	0.5	0.6	0.6
0.5	0.5	0.7	0.8	0.8	0.6	0.6	0.7	0.6	0.8
0.7	0.8	0.8	0.8	0.9	1.0	0.8	0.9	0.9	0.9
1.0	1.1	1.3	1.1	1.1	1.2	1.2	1.1	1.1	1.3

Thickness 5 mm		50 kV			60 kV			90 kV	
drill		mAs			mAs			mAs	
diam.	10.0	20.0	40.0	10.0	16.0	25.0	3.2	5.0	10.0
0.3	0.7	0.8	0.9	0.8	0.8	0.5	1.0	0.9	0.9
0.5	1.0	1.1	0.7	0.8	0.9	0.9	1.0	1.0	0.8
0.7	1.1	1.0	0.9	1.1	0.9	1.0	1.1	1.1	0.9
1.0	1.5	1.5	1.4	1.3	1.3	1.4	1.8	1.5	1.3

Thickness 8 mm		50 kV			60 kV			90 kV	
drill		mAs			mAs			mAs	
diam.	10.0	20.0	40.0	10.0	20.0	40.0	3.2	5.0	10.0
0.3	0.7	0.7	0.4	0.5	0.4	0.8	0.5	0.7	0.4
0.5	1.0	0.8	0.6	0.9	0.8	1.4	0.5	0.7	0.9
0.7	0.9	1.1	1.1	1.1	1.0	1.2	1.4	1.3	1.2
1.0	1.5	1.6	1.3	1.6	1.6	1.4	1.2	1.8	1.6

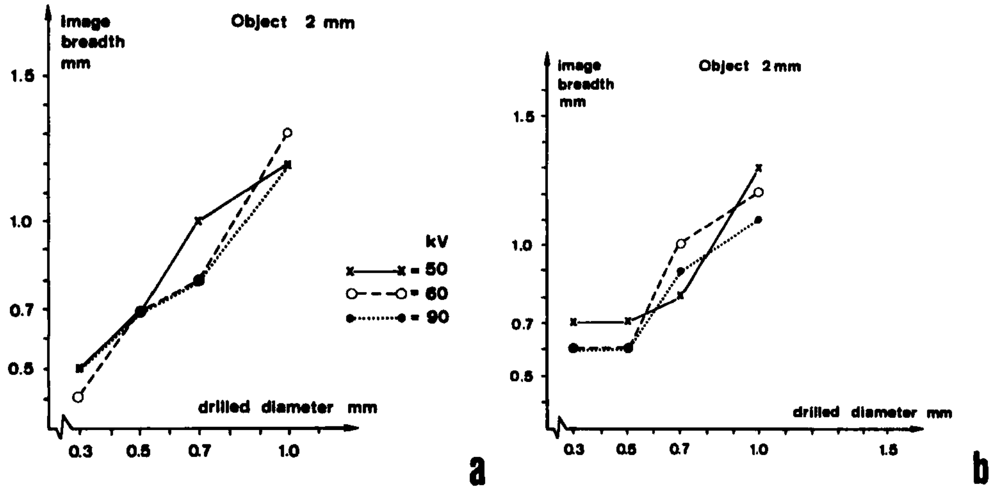

Fig. 3. The relation between drill diameter (abscissa) and the densitometrically measured canal diameter (ordinate) for a dentine object 2 mm in outer diameter. a = without bone phantom, b = with bone phantom.

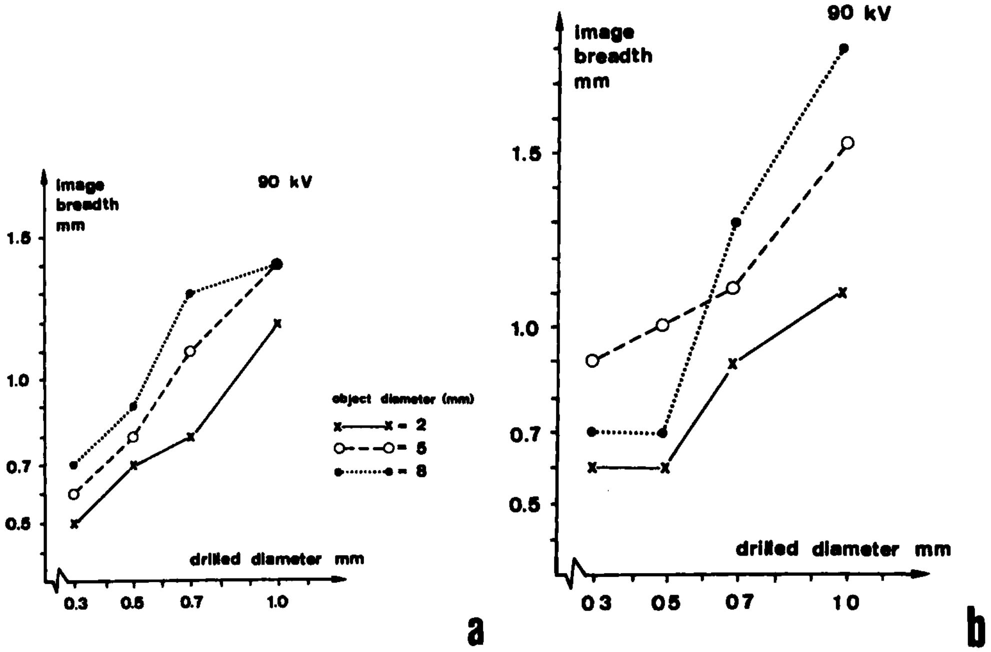

Fig. 4. The relation between drill diameter (abscissa) and the densitometrically measured canal diameter (ordinate) and tube voltage 90 kV. a = without bone phantom, b = with bone phantom.

for »optimally» exposed films, showing how different tube voltages and differences in outer cone diameter may affect the results. Comparison of different dentine thicknesses (as in Fig. 4) shows that the thicker objects, intended to simulate bigger roots, gave relatively wider breadths of all canal dimensions. For the narrowest object (2 mm) the additional breadth amounted to 0.1—0.2 mm, whereas for the thickest object (8 mm) it was approximately 0.4 mm, sometimes more. The results of measurements of breadth for the objects investigated with the same object-film distance showed largely the same as in Table I, that is, the diameter measured densitometrically was larger than that drilled. The thicker cones produced a wider canal image than did the narrower.

The differences in substance (canal depth) expressed in mm Al for the images of the different test bodies with and without the bone phantom are shown in Tables III and IV. It is seen that a few overexposed or underexposed films gave values which tended to be high. Regardless of whether or not the bone phantom was used, the parallel cones with the smallest outer dimensions gave the lowest values for a given canal diameter. The values obtained with the medium-sized and largest cones, with outer diameters 5 mm and 8 mm respectively, were virtually the same. Figure 5 shows a graphic representation of an example from Tables III and IV of the »optimal» films obtained at a tube voltage of 60 kV.

The results obtained when the root canal contrast was expressed in ODU showed, as expected, that a tube voltage of 50 kV gave the highest values in most cases. The effects of exposure factors on the image contrast are shown in Figure 6 for an object with an outer diameter of 5 mm.

Table III. *Maximal substance difference (in mm Al) between the center of a canal and the dentine walls for dentine objects with different outer dimensions*

Thickness 2 mm	50 kV			60 kV			90 kV		
drill	mAs			mAs			mAs		
diam.	2.5	5.0	10.0	0.8	2.5	5.0	0.8	1.6	2.4
0.3	0.07	0.07	0.07	0.08	0.13	0.09	0.06	0.17	0.15
0.5	0.19	0.14	0.17	0.11	0.16	0.25	0.26	0.21	0.16
0.7	0.20	0.25	0.33	0.17	0.27	0.29	0.37	0.23	0.22
1.0	0.24	0.33	0.35	0.33	0.38	0.34	0.40	0.29	0.32

Thickness 5 mm	50 kV			60 kV			90 kV		
drill	mAs			mAs			mAs		
diam.	5.0	10.0	20.0	2.5	5.0	10.0	1.6	2.4	4.0
0.3	0.15	0.10	0.13	0.19	0.13	0.14	0.19	0.13	0.17
0.5	0.29	0.28	0.33	0.29	0.30	0.29	0.27	0.23	0.21
0.7	0.34	0.38	0.58	0.45	0.39	0.52	0.34	0.44	0.56
1.0	0.57	0.62	0.73	0.51	0.58	0.76	0.66	0.63	0.69

Thickness 8 mm	50 kV			60 kV			90 kV		
drill	mAs			mAs			mAs		
diam.	5.0	10.0	20.0	2.5	5.0	10.0	1.6	2.4	4.0
0.3	0.19	0.20	0.17	0.23	0.19	0.18	0.15	0.22	0.12
0.5	0.36	0.24	0.22	0.45	0.25	0.22	0.29	0.23	0.27
0.7	0.49	0.30	0.32	0.62	0.37	0.37	0.56	0.36	0.36
1.0	0.51	0.58	0.51	0.68	0.64	0.57	0.77	0.51	0.44

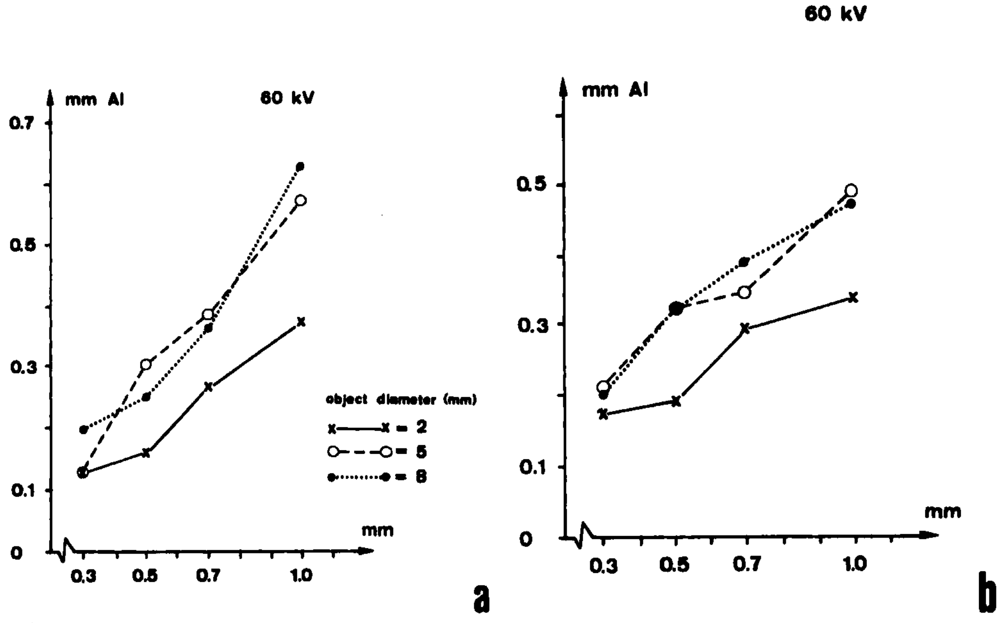

Fig. 5. Densitometrically measured difference in substance between the canal lumen and the dentine walls expressed in mm Al (ordinate) for films of objects with different canal diameters and different outer dimensions. Tube voltage 60 kV. a = without bone phantom, b = with bone phantom.

Table IV. *Maximal substance difference (in mm Al) as in Table III but with the dentine object enclosed in a bone phantom*

Thickness 2 mm		50 kV			60 kV			90 kV	
drill		mAs			mAs			mAs	
diam.	10.0	20.0	40.0	10.0	16.0	25.0	2.4	3.2	5.0
0.3	—	0.15	0.16	0.18	0.17	—	0.15	0.15	0.15
0.5	0.12	0.17	0.19	0.22	0.19	0.14	0.19	0.19	0.21
0.7	0.28	0.28	0.32	0.23	0.29	0.18	0.30	0.22	0.32
1.0	0.35	0.50	0.42	0.41	0.34	0.30	0.37	0.35	0.36

Thickness 5 mm		50 kV			60 kV			90 kV	
drill		mAs			mAs			mAs	
diam.	10.0	20.0	40.0	10.0	16.0	25.0	3.2	5.0	10.0
0.3	0.29	0.20	0.13	0.14	0.21	0.18	0.29	0.30	0.20
0.5	0.46	0.29	0.33	0.29	0.32	0.26	0.29	0.35	0.27
0.7	0.38	0.37	0.32	0.30	0.35	0.35	0.37	0.40	0.41
1.0	0.54	0.45	0.49	0.43	0.49	0.51	0.53	0.62	0.50

Thickness 8 mm		50 kV			60 kV			90 kV	
drill		mAs			mAs			mAs	
diam.	10.0	20.0	40.0	10.0	20.0	40.0	3.2	5.0	10.0
0.3	0.29	0.29	0.13	0.20	0.20	0.17	0.13	0.13	0.10
0.5	0.25	0.31	0.26	0.33	0.32	0.36	0.25	0.32	0.43
0.7	0.33	0.30	0.29	0.31	0.39	0.38	0.41	0.39	0.37
1.0	0.37	0.31	0.36	0.42	0.47	0.49	0.65	0.47	0.48

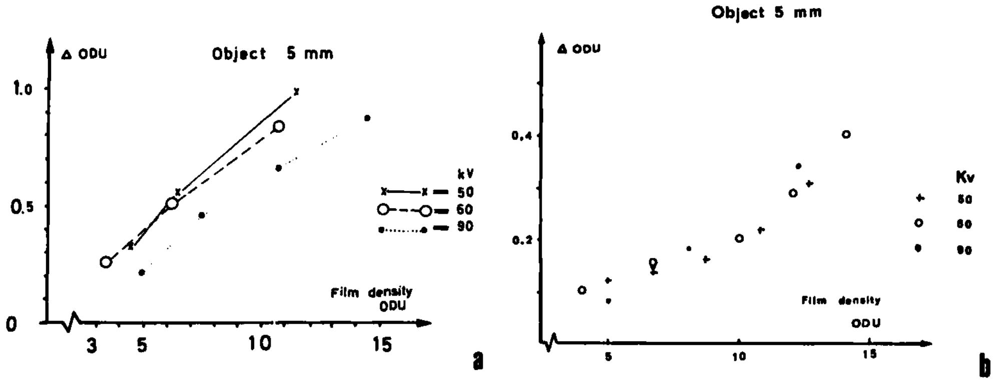

Fig. 6. Difference in film density in ODU between the canal (drill diameter 0.7 mm) and the dentine walls in relation to the density of the film. a = without bone phantom, b = with bone phantom.

In the films exposed without the bone phantom, 90 kV gave the lowest, *i.e.* poorest, values. The values obtained at 50 and 60 kV were the same. When the bone phantom was used, tube voltage appeared to have very little influence. The results for the other objects were in general the same. In all cases it was clear that there was greater image contrast as the average photographic density increased.

The effect of the thickness of the object was also determined in films obtained at the tube voltage of 60 kV and having equal film density in the image of the dentine nearest to the canal. For all canal dimensions except 0.3 mm a dentine thickness of 5 mm yielded the highest values. (Results not printed in this article may be obtained from the author).

Figure 7 shows how it is possible, on the basis of the dentine profile, to calculate the transmission and blackening of the film and the resulting densitometer reading in the type of experiment described above. The results were calculated for two dentine cones differing in thickness (2.0 and 8.0 mm) but with the same canal dimension (1.0 mm) roentgenographed at a tube voltage of 60 kV. The experimental results are shown in the lower curve.

For the construction of these theoretical

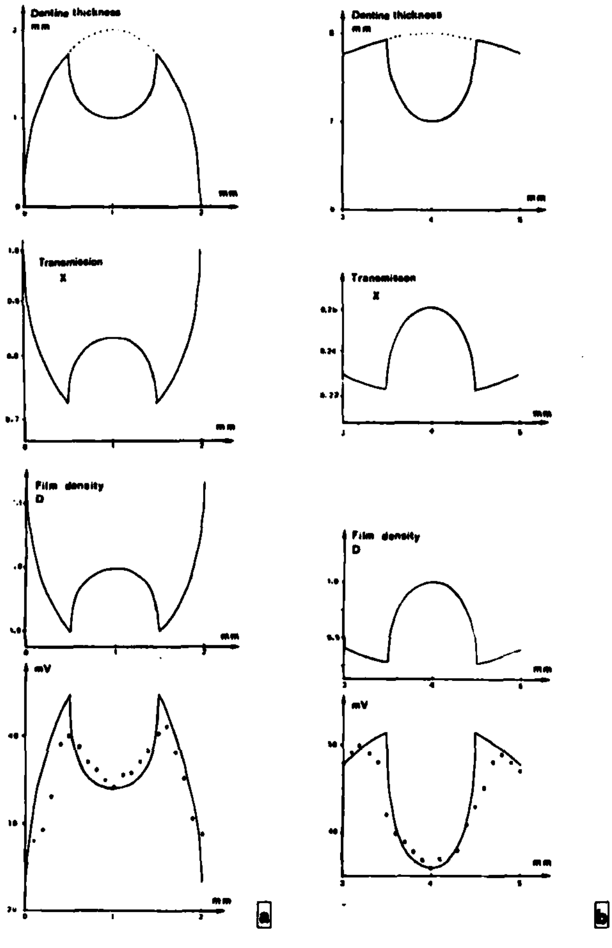

Fig. 7. Dentine thickness, radiation transmission, film density and densitometer readings theoretically calculated for a 1.0 mm canal and outer cone diameters 2.0 and 8.0 mm (left and right). In the lowest curve, empirical results are shown (dotted).

curves, the following equations have been used. The reader is also referred to *Hedin et al.* (1974).

$$X = X_o \cdot e^{-\mu_d \cdot d}$$

$$D = \gamma_D \cdot \log X$$

$$I = I_o \cdot 10^{-D} = I_o \cdot 10^{-0.15\ \mathrm{ODU}}$$

$$mV_x = mV_{x_o} \cdot 10^{1.15} \cdot D = mV_{x_o} \cdot$$

$$\cdot\ 10^{0.172\ \cdot\ \mathrm{ODU}}$$

Symbols:

X = roentgen transmission through the dentine object

X_o = roentgen transmission outside the dentine object

μ_d = the effektive linear attenuation coefficient (cm^{-1}) for dentine thickness and a given tube voltage

d = dentine thickness

D = density of the film

γ_D = film contrast for density D

I = intensity of transmitted light

I_o = intensity of incident light

ODU = the difference in blackening between two fields on a photographic control scale (theoretical ODU = 0.15 D)

mV_x = the densitometer reading at a point in the object

mV_{x_o} = the densitometer reading outside the object

DISCUSSION

When objects were roentgenographed without the bone phantom, large differences in exposure were required for dentine cones of different thickness to produce the same film density. Clinically one does not have the impression that the thin parts of roots are overexposed and, in experiments in which the bone phantom was used, the thickness of the dentine cone had less effect on the exposure required for the desired film density. The blackening relief obtained was the same regardless of whether the bone phantom was used.

In order to simulate clinical conditions, the focus-film distance was fairly long (34 cm), with the result that the emergent beam of radiation came to contain a group of nearly parallel rays which improved the reproduction of the object. The differences in object-film distance had no significant effect on the geometric enlargement, as a simple mathematical calculation will show.

The measurements of canal breadth (Tables I and II) consistently exceeded the corresponding drill diameters. The difference was greater than could be explained by the discrepancy between drill diameter and measured canal diameter (*Hedin et al.*, 1974). It was due in part to a systematic error in the method of measurement. The field of film read had a definite diameter (0.2 mm), and if only a part of the circular area was darkened, the photometer reading decreased. The outer dimensions of the canal, assumed to correspond to the highest densitometer readings, thereby came to be erroneously displaced at least 0.1 mm peripherally on each side. This error cannot be eliminated by reducing the size of the field, since if the field is too small individual silver grains could begin to exert an effect.

Why were the values obtained for a given canal diameter higher for thicker cones than for narrower ones? A possible explanation may be provided by the edge spread function currently in use, which in part replaces the earlier so-called penumbra formation. Edge spread function is a result of the size of the focus, extrafocal radiation and scattering of radiation within the object. The transition from one darkened field to another is not abrupt, giving a sharp boundary of roentgen relief, but is S-shaped. The slope of the »S» depends on the factors mentioned. Figure 7 shows how in a narrow object (2 mm) the maximal measured millivoltage falls fairly close to the theoretically correct value, whereas in a thick object there is a bilateral peripheral displacement which results in a larger calculated canal diameter. Since the dentine profile has a steep slope in the narrow object, the curve of this profile limits the outer swing of the »S»

The precision ($S.D._k$) of the densitometer in double determinations of the canal breadth was previously calculated to be 0.13 mm independent of the canal breadth (*Hedin et al.*, 1974). This took into account such factors as inhomogeneity of the dentine, variations in the thickness of the film emulsion and variations in development and light measurement. Together, these sources of error played a role, but not a dominant one. Compare the left and right sides of the experimental curve at the bottom of Figure 7.

One might expect that the measured canal breadth would be affected by the tube voltage, since the latter determines the amount of scattered radiation. However, this seemed to have no significant effect in the present study. According to *Degering* (1964), the images of radiopaque structures on underexposed films have outlines that correspond to reality, whereas they are diminished on dark-density films. According to this, the pulp space should appear to be larger on dark films. As seen from Tables I and II, the densitometrically determined breadths of the drilled canals in this study were the same regardless of whether they were over- or underexposed. *Degering's* measurements, however, were not done with a densitometer, but were based on visual estimates of the outline forms on roentgenograms, a method in which increased blackening would yield the reported result.

The differences in substance due to the presence of the drilled canals in the dentine test objects were reported in mm Al. It would not be expected that these values would differ with different exposures, since the blackening of the steps of the penetrometer was altered in the same way on the films. That a few films in this study, mainly underexposed, yielded values that differed from those obtained from the »optimally» exposed films may be due to greater error in measurement on very light films (*Hedin et al.*, 1974).

The average photographic density in the film had a marked effect on the image contrast between the canal and the dentine walls measured in ODU as was expected. As shown in Figure 6, a tube voltage of 90 kV gave less contrast than did 50 or 60 kV. When the dentine object was roentgenographed within the bone phantom, there was no difference between the results obtained at different tube voltages, perhaps because of the filtration effect exerted by the artificial »bony» plates.

As mentioned above, the blackness of the reference stepwedge changed not only with exposure time, but also when the tube voltage was changed from 50 to 60 to 90 kV. The contrast obtained at the different tube voltages cannot be compared in terms of mm Al. However, these values can be used for purposes of comparison if an ideal relation between mm Al and ODU is established for each tube voltage and exposure (mAs). One must assume that the appearance of the object remains the same or that only a part of the radiation produces its roentgen image. If the degree of blackening of the film is known, such a curve or conversion factor can be used to recalculate the inherent blackening of the object from mm Al to ODU, which is the unit observed on the individual roentgenogram. At the same time, the results become independent of factors concerned with the film or its development.

The differences in both substance and image contrast obtained with and without the use of the bone phantom were generally lowest for the parallel cones with the smallest outer diameter (Tables III and IV). The explanation is illustrated in Figure 7 a and b. Even the difference in dentine substance between the center of the canal and its walls was less for the small objects because of their curvature. For the smallest object (2 mm) the thickness of this cross-section of dentine calculated 0.1 mm peripheral to the maxima would need to be multiplied by at least 1.1, 1.2 and 1.7 for the 0.5, 0.7 and 1.0 mm objects respectively in order to be comparable to the values which would be obtained if the curvature of the cone were negligible. The effect was less for the other objects and did not exceed 4 %. The same conclusion applies to the curves of millivoltage at the bottom of Figure 7. This source of error would have been eliminated if the canals had been drilled in plane objects, but similarity to natural tooth roots would have thereby been lost.

The precision (S.D.$_k$) of double determinations of differences in substance and image contrast carried out in this way has previously been calculated to 0.05 mm Al and 0.03 ODU respectively. These determinations include the same sources of random error as the measurements of canal breadth mentioned above. It is obvious that random errors cannot be of major importance for the results. In addition to the systematic error due to curvature of the cones, scattering of radiation, the geometric enlargement factor and the error of reading in a large field, mention may be made of the possible error due to intermittent rather than continuous reading. This was not analysed. The applicability of the results to natural teeth will be discussed in a forthcoming publication.

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