dental radiology

The optimum circular field size for dental radiography with intraoral films

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Intraoral radiographs are often made with circular fields to irradiate the film, and in many instances these fields are much larger than the film. The feasibility of reducing a circular radiation field without increasing the probability of excessive cone cutting was evaluated clinically, and an optimum field size was determined. A circular radiation field 4.5 cm. at the tube end was found to minimize cone cutting and reduce the area of tissue irradiated by at least 44 percent. Findings suggest that current I.C.R.P. recommendations for a 6 to 7.5 cm. diameter circular field may be too liberal.

For dental purposes, intraoral radiographs are often made with circular fields to irradiate the film. Since these fields are much larger than the surface of the film, radiation hygiene can be improved by reducing the field diameter. Reducing the radiation field, however, increases the probability of cone cutting due to inaccuracies in aligning the beam with the film and will potentially result in more retakes and increased irradiation of the patient. Because of these two tendencies, it is desirable to determine whether an optimum field size can be found which will minimize cone cutting and reduce patient exposure. The purpose of this investigation is to clinically evaluate relationships between beam and film alignment along with other factors influencing the determination of an optimum field size.

For conventional dental radiography using intraoral films and circular fields, the area of the x-ray beam at the film plane is much larger than the surface of the film. The International Council on Radiation Protection has attempted to reduce the area of the face irradiated[1] by establishing limits to the diameter of the circular field. The use of rectangular collimators has proved very effective in further reducing irradiation of the patient.[2] However, circular fields are still commonly used, and only those factors related to establishing the optimum beam diameter for a circular field will be discussed here.

The area of a circular field increases with the square of its diameter (D) and is expressed mathematically as $0.25\pi D.^2$ The relationship between the diameter of the field and the area is shown by curve a in Fig. 1,a. Since the amount of radiation to which the patient is exposed is proportional to the area irradiated, it is of prime importance to reduce the diameter of the field as much as possible. Reduction of the field, however, increases the probability of cone cutting caused by inaccuracies in aligning the beam and film and may result in retakes. The relationship between the field diameter and the percentage of films showing cone cutting is illustrated in curve b, Fig. 1,a; this curve can be found only by experimental clinical methods. It is obvious that cone cutting will occur in all cases (100 percent) when the field diameter is equal to, or smaller than, the diagonal (N) of the film. If it is assumed that every film with cone cutting results in

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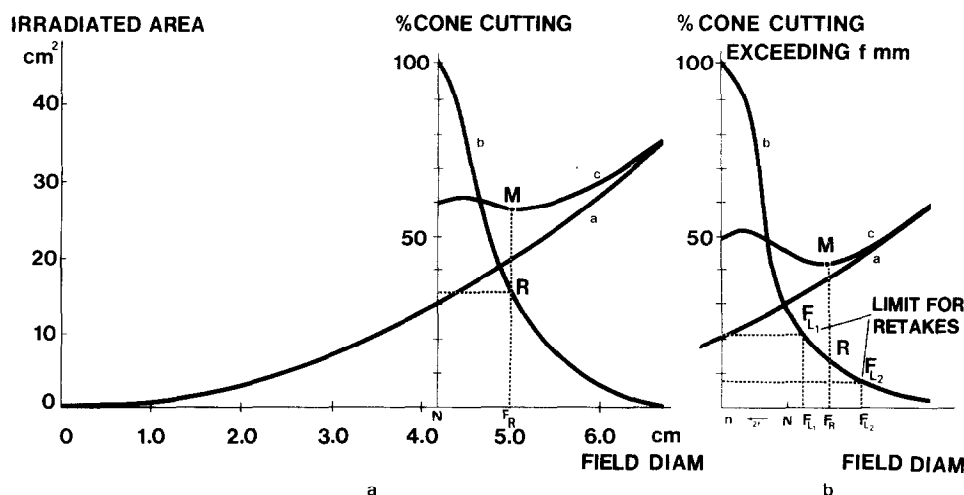
Fig. 1. Graphs illustrating the method used to determine the optimum field size. *Curve a,* Relationship between the diameter of the x-ray beam at the film site (field diameter) and the irradiated area. *Curve b,* Relationship between the field diameter and the percentage of films showing cone cutting. *Curve c,* Average irradiated area for each field diameter allowing for one retake per cone cut. *N,* Diameter of the circle circumscribing the film. *M,* Minimum in curve c indicating the smallest average irradiated area. *R,* Percentage of films with cone cutting for the minimum irradiated area. F_R, Field diameter for the minimum average area of irradiation with an acceptable percentage of retakes. L_1, An arbitrarily chosen maximum acceptable percentage of retakes which is not exceeded for the optimum field diameter M. L_2, An arbitrarily chosen maximum acceptable percentage of retakes determining the optimum field diameter. F_{L1}; F_{L2}, The field diameters found when the chosen limit for retakes are L_1 or L_2, respectively. *f,* The maximum amount of cone cutting acceptable before a retake is required. $n = N - 2f$, The minimum field diameter when f mm. of cone cutting is acceptable.

one retake, it is possible to calculate from curves *a* and *b* the average irradiated area for every field diameter evaluated, curve *c* in Fig. 1,*a.* Notice that the use of a large field resulted in a proportionately larger amount of tissue being irradiated at the initial exposure but required a smaller number of retakes; on the other hand, a small field resulted in less tissue irradiation initially but required more retakes. These opposing tendencies resulted in a minimum (M) value in the curve *c,* corresponding to the smallest field diameter compatible with a low percentage of retakes.

Graphically, these values are determined by following the vertical broken line from *M* to *R* (percent cone cuts) and to F_R (field diameter) in Fig. 1,*a.* The preceding illustrates the principles for finding the optimum field size; three additional aspects concerning retaking of films will be considered in more detail: (1) the severity of the cone cut related to the beam diameter; (2) defining an "acceptable" number of retakes; (3) defining criteria for retaking of cone cuts.

In calculating the relationship between the field diameter and the average area of tissue irradiated, it was assumed that films with cone cutting resulted in only one retake. However, it is obvious that a field

diameter a few millimeters larger than the smallest possible beam diameter (the diagonal dimension of the film) will result in a very high percentage of films showing excessive cone cutting, and in such cases it is probable that one retake will not always be sufficient. When progressively larger field sizes are used, a greater number of films will be produced with less extreme cone cutting, and one retake may be sufficient to correct the error. As will be shown later, the optimum field size should produce 5 to 17 percent retakes with the reasonable assumption that only one retake would be needed to correct a cone cut.

It can be concluded that the smallest field diameter compatible with a low number of cone cuts (*M,* Fig. 1,*a*) will still cause a certain percentage of retakes *(R);* it therefore becomes necessary to establish a practical limit for the percentage of retakes deemed acceptable. The maximum acceptable percentage of retakes must be determined by clinical judgment. For this investigation, two different arbitrary values of the limit for retakes due to cone cutting, L_1 and L_2, were chosen (Fig. 1,*b*). Limiting the permissible number of retakes to L_1 or L_2 effectiveness diminishes the choice of optimum field sizes to F_{L1} or F_{L2} (Fig. 1,*b*).

The third factor in selecting an optimum beam
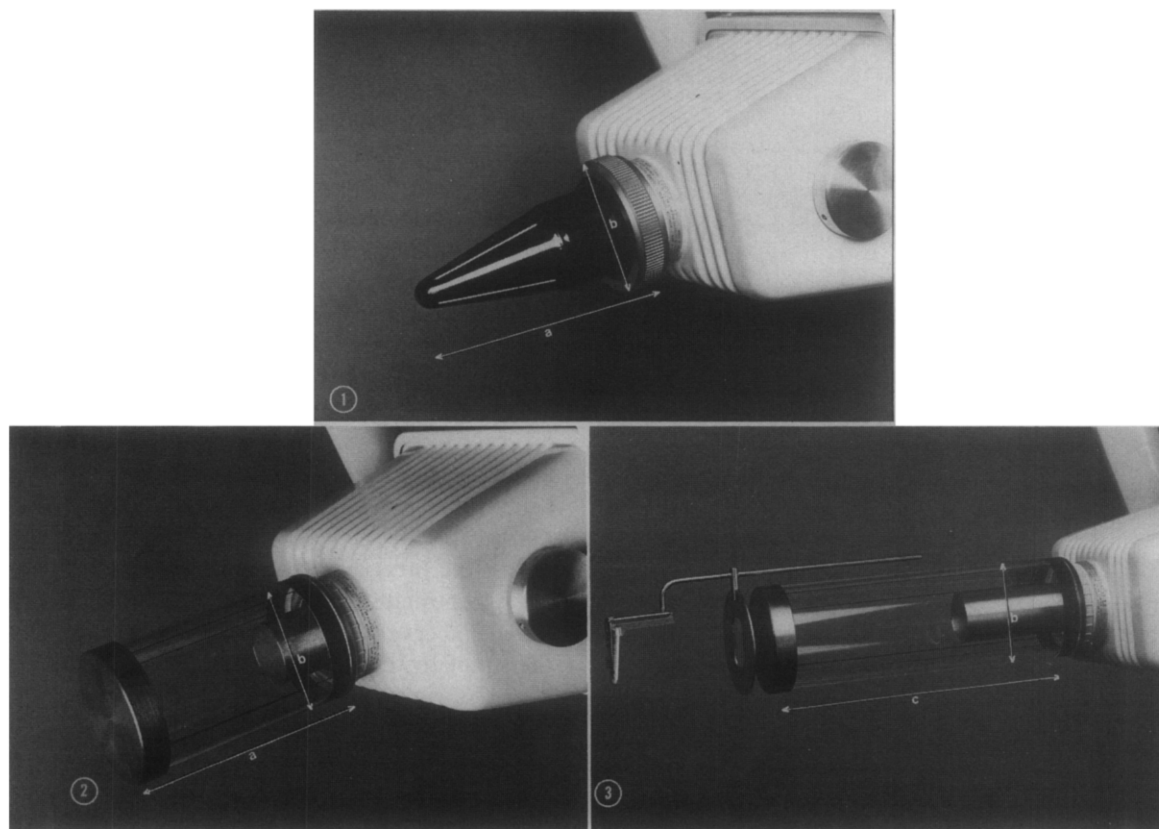
Fig. 2A. Shape of the position indicating devices and provisions to identify the beam axis. *1*, Short cone; focal spot to cone end distance, 20.5 cm. *2*, Short tube; focal spot to cone end distance, 20.5 cm. *3*, Long tube; focal spot to cone end distance, 30.5 cm.

diameter is the relationship between the amount of cone cutting and the need for a retake. Not all cone cuts will result in a retake because (1) a small cone cut on a peripheral area of the film will be covered by the 1.75 mm edge of the film mount; (2) the edge of the irradiated area next to the cone cut may not be a sharp line but will show focal unsharpness and, consequently, it is difficult to define exactly where cone cutting starts; (3) small amounts of cone cutting affect only the corners of the film and may not always affect diagnostic and interpretative value of the radiograph.

Considering these three arguments, it can be concluded that a small arbitrarily defined amount (f. mm.) of cone cutting would not require a retake, and consequently the vertical axis denoted at field diameter *N* in Fig. 1,*a* at which 100 percent of films will be cone cut should be shifted 2f mm. to the left to *n* (Fig. 1,*b*). The resultant shift will permit the determination of a new curve, *b*, which now depicts the percentage of films in which cone cutting exceeding f mm. could be observed and represents a clinically acceptable percentage of retakes. If N is the diagonal of the film, n is equivalent to N-2f. Note that shifting
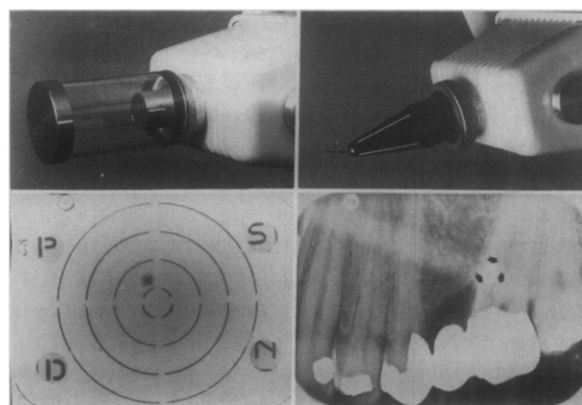
Fig. 2B. Examples of beam axis identification on a radiograph. *Left,* Using the pinhole diaphragm. *Right,* Using the lead bead and a wire cross.

curve *b* in Fig. 1,*b* to the left produces a change in shape and permits calculation of a new curve *c* with a new minimum, *M*.

In summary, the main parameter to be used in determining an optimum field diameter has to be the operator's ability to orientate the beam axis to the
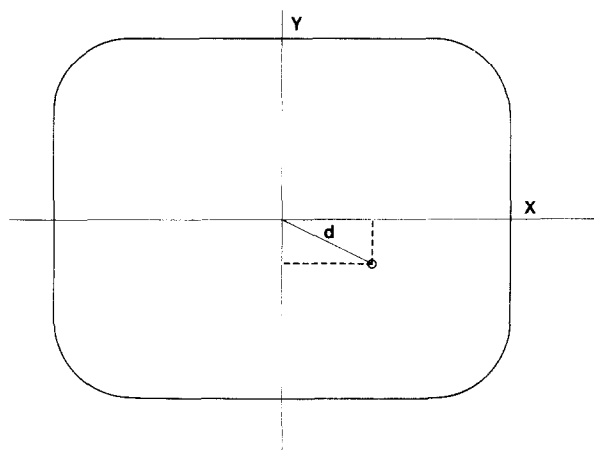
Fig. 3. The X and Y coordinate system on the x-ray film and the distance d.

center of the x-ray film; this ability ultimately determines the slope of *b* in Fig. 1,*b* and can be studied clinically by measuring the misalignment of the cone/tube and film. Misalignment of the cone/tube and film will depend on the following factors: (1) the x-ray machine's handling ease, (2) the types of patients and their ability to cooperate, (3) the operator's skill and experience, (4) the region to be radiographed, and (5) the alignment of the beam, including the shape of the beam-indicating device and the use of external beam-aligning and film-holding devices.

The last three factors were considered to be of primary importance in determining optimum field diameter and required answers to the following questions: (1) When the x-ray field and film are aligned for a clinical radiograph, how accurately does the center of the field correspond to the center of the film? If the center of the field and the film do not correspond, what is the spatial distribution of these points? Are they distributed in a mathematically predictable way? (2) Does the region to be radiographed affect the alignment of the beam axis to the center of the film? (3) Do various beam- and film-alignment procedures and/or devices affect the accuracy of the film and x-ray field alignment? (4) Can alignment of the x-ray field and film be improved by experience? (5) What is the optimum field diameter?

MATERIALS AND METHODS

The following position-indicating devices were investigated: a short-pointed cone, a short parallel tube, and a long parallel tube (Fig. 2*A*). The short position-indicating devices were used for radiographs using the bisecting-angle principle, while the long

tube was always used with an alignment device[2] and the paralleling principle.

To record the intersection of the beam axis relative to the center of the x-ray film, called "point of impact," two different methods were used. The first method identified the beam axis without producing a complete radiograph of the area by closing the aperture of the x-ray tube with a metal plate containing a 0.6 mm. diameter opening in the center. Subsequent exposure of a film produced a black spot on an otherwise clear radiograph indicating the location of the beam axis. This system permitted identification of the beam axis but prevented the operator from using the correct vertical and horizontal angulation (Fig. 2*B*, left). The second method identified the beam axis on completely exposed radiographs by means of a wire cross attached to the end of the tube. The center of the wire cross on the radiograph indicated the position of the beam axis. For the short-pointed cone, a lead bead attached to the tip of the cone was used instead of a wire cross (Fig. 2*B*, right).

Points of impact were recorded by measuring their positions relative to X and Y coordinates constructed over the center of the film. The direction of the coordinates was chosen parallel with the borders of the film (Fig. 3, dotted lines). The distance from the point of impact to the origin was also measured (distance d).

Two different film sizes were used; film size 1 for maxillary and mandibular anterior regions and film size 2 for premolar and molar regions. Six groups of operators made a series of exposures under a variety of different conditions shown in Table I. To find the optimum field diameter, it was necessary to define the maximum acceptable cone cutting before a retake would be needed (f); this limit was set at 2 mm., and the percentage of retakes was limited to a maximum of 20 percent. The procedure used for finding the optimum field diameter was as follows:

1. Determine the curve for the irradiated area as a function of the field diameter, given by $0.25\pi D^2$, curve *a* in Fig. 1.
2. Select the maximum cone cutting acceptable before a retake is needed (2 mm.).
3. Determine the film sizes to be used and find the diagonal of each film (N): Film size 1 = 42 mm.; film size 2 = 46 mm. (Fig. 1, *a* and *b*).
4. Reduce the diagonal (N) by twice the maximum acceptable cone cutting. This defines placement of the vertical axis (n = N − 4 mm.) from which the curve starts with 100 percent retakes (film size 1 = 38 mm.; film size 2 = 42 mm.).
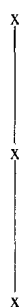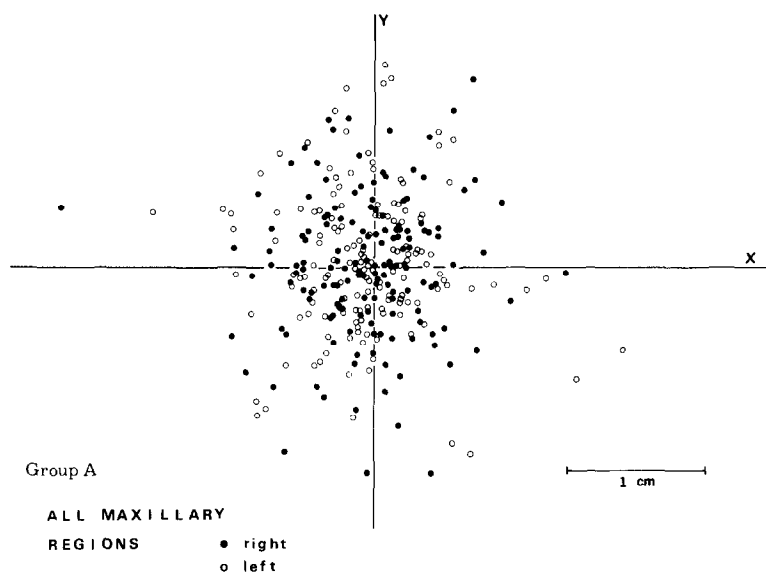
Fig. 4. Distribution of the point of impact on the x-ray film for group A. All areas, maxillary left and right separately.
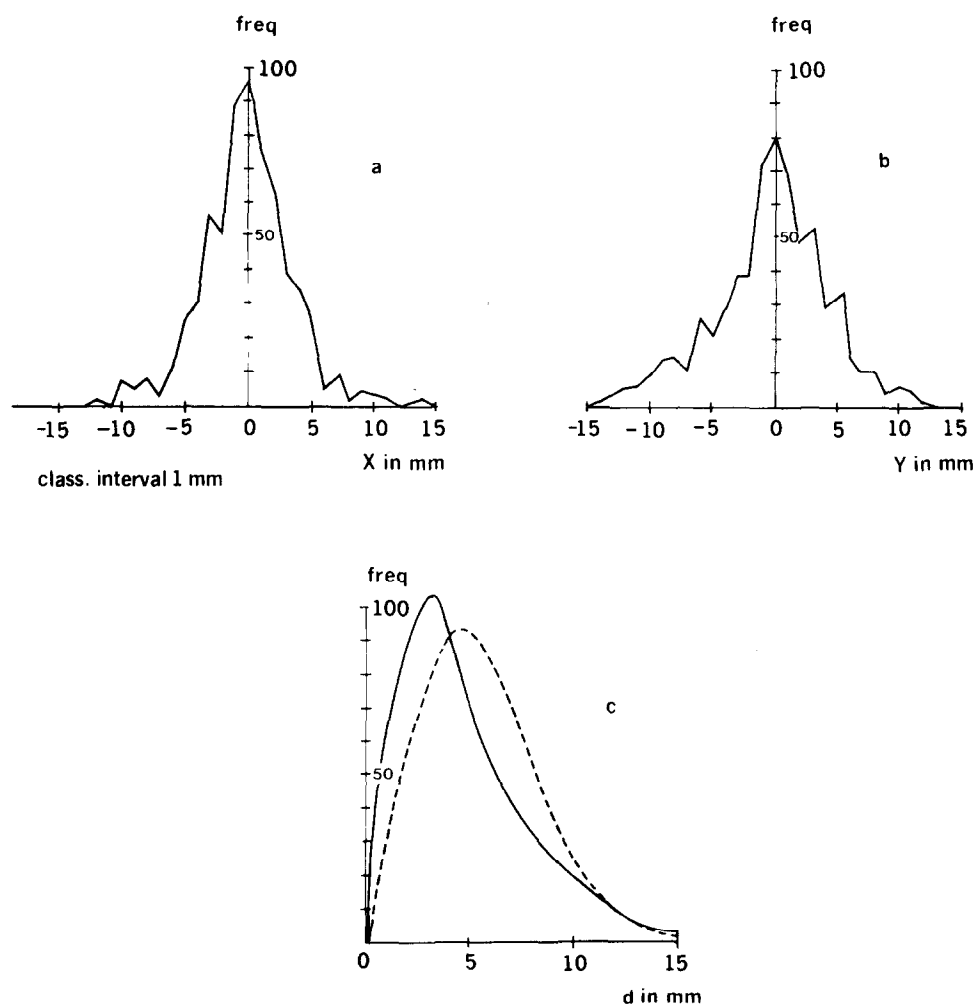
Fig. 5. **a** and **b**, Distribution of X and Y for a class interval of 1 mm. **c**, Distribution of d as found in the sample (solid line) and for a normal χ^2 distribution (broken line).

Table I. Conditions of the different experiments and the combination of conditions used to answer the different questions

Group of operators	*No. and kind of operators*	*No. of sessions (with series of exposures)*	*Intermission (days)*	*Type of patient*	*Area radiographed*	*No. of exposures per session*			*Spatial distribution*
						Δ	□	Long-tube	
A	40 dental students with some experience	1	—	Phantom	Full-mouth	● 16			X
B	10 dental students without experience	8	7	Patient*	Full-mouth	● 16	● 16		X
C	10 dental students without experience	6	7	Patients	Maxillary molar	2	2		X
D	24 dental students without experience	1	—	Patients	Mandibular anterior / Maxillary molar			● 1 / ● 1	
E	18 dental hygienists without experience	5-7	7	Patients	Maxillary molar			● 1	
F	10 dentists, general practitioners	5-7	1	Patients	Maxillary molar	⊙ 1	⊙ 1	● 1	

Δ = Bisecting-the-angle technique using a short-pointed cone.
□ = Bisecting-the-angle technique using a short tube.
▯ = Long-tube paralleling technique with the use of an aligment device.
● = Marking of the beam axis on the film using the pinhole diaphragm.
⊙ = Marking of the beam axis on the film using a cross wire (Fig. 2B).

*The patient was a student, and for the complete series of exposures the amount of radiation was equivalent to one tenth of the radiation needed for a single intraoral radiograph with a field diameter of 6 cm. at the film site.

5. Determine the probability for retakes (percent retakes) when the cone cutting exceeds f mm. (f = 2 mm.). This probability is a function of the field diameter and can be determined only by clinical experimentation, curve b in Fig. 1,*a* and *b*.

6. Determine from curves *A* and *B* the average irradiated area expressed as a function of the field diameter (curve *c* in Fig. 1,*a* and *b*).

7. Identify the minimum irradiated area (M) on curve *c* in Fig. 1,*a* and *b*.

8. Find the percent of retakes belonging to this minimum irradiated area (R) (Fig. 1,*b*).

Example 1: If the percentage of retakes is below

the maximum acceptable percentage (L_1, Fig. 1,*b*), the optimum field diameter F_R may be identified. Field diameter F_R identifies the minimum irradiated area corresponding to an acceptable percentage of retakes.

Example 2: If the percentage of retakes exceeds the maximum acceptable value (L_2), curve b has to be followed downward along its slope until it intersects with the limit for retakes L_2 in Fig. 1,*b*. From this point, the corresponding field diameter may be found (F_{L2}). This field diameter results in an irradiated area larger than the more desirable minimum (M); however, it becomes necessary to achieve a trade-off between field size and cone cuts requiring

Combination of conditions used to solve problem no.

2 Area	3 Alignment aids	4 Operator experience	5 Optimum field
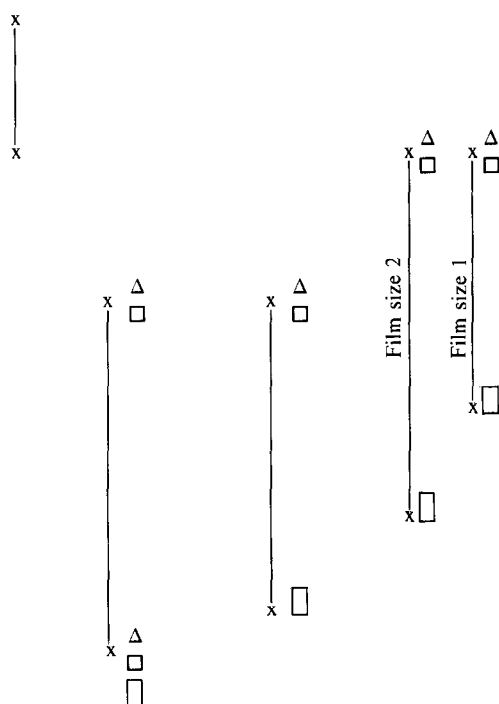
retakes, and a preference is given to minimizing the number of potential retakes by using a slightly larger field diameter.

RESULTS
The spatial distribution of the beam axis point of impact on x-ray films

The distribution of the point of impact for all radiographs taken of the maxillary arch by students in group A of Table I are shown in Fig. 4. The frequency distribution of all points of impact at various distances from the ordinate of the X and Y coordinate is shown in Fig. 5, *a* and *b* for radiographs of all regions of the maxilla and mandible. The corresponding distribution of the distance (d) from the ordinate is shown in Fig. 5, *c* by a solid line. Preliminary expectations anticipated that the points of impact would follow a normal statistical distribution; a test for normality was applied to D, which should follow a χ^2 distribution (Fig. 5, *c*, broken

line). A statistical test (see Appendix) demonstrated that the distribution of the point of impact did not follow a normal Gaussian distribution. The spread of the impact points can be described as showing a symmetrical tendency with a peak centered at the average; this tendency for symmetry was stronger than a normal Gaussian distribution and resulted in a leptokurtosis.

The distribution of the relative frequencies of d found in Groups A, B, and C of Table I for the maxillary molar region is given in Fig. 6 and illustrates the similarity in the point of impact distribution irrespective of the differences between these groups. Group A operators had to align the beam to a film positioned in a phantom head; the films were exposed by a 0.6 mm. diameter beam, and consequently the operator was exempted from having to use correct vertical and horizontal angulation. Group B alignment conditions were the same as those of Group A, except that exposures were made on a patient. Group C operators aligned the cone to the film but had the additional task of producing an acceptable radiograph using the correct vertical and horizontal angulation. Although a precise similarity between groups did not exist, the differences in conditions were not so extreme as to prohibit the use of the average and the variance determinations to evaluate the results, and in one instance the F test was used because of its applicability to data following a semi-normal distribution, Table II. (See Discussion.)

The spatial distribution of point of impact for different regions and different groups

When the results are separated for different regions of the mouth, it can be observed that the standard deviation of the coordinates varies with the region and with the directions X and Y (Fig. 7,*a* and Table II). The largest standard deviations were found for the maxillary molar region, where the distribution and spread of these points of impact can be observed in Fig. 8A. The smallest difference in the point of impact distribution along the X axis was found in the mandibular incisor region and is illustrated in Fig. 8B. Interestingly, the largest difference between S_x and S_y was observed in this region.

A combined estimate of the variance (s_{xy}^2) can be made by combining the variances in the X and Y direction,

$$s_{xy}^2 = \frac{\Sigma\, d^2}{2n}.$$

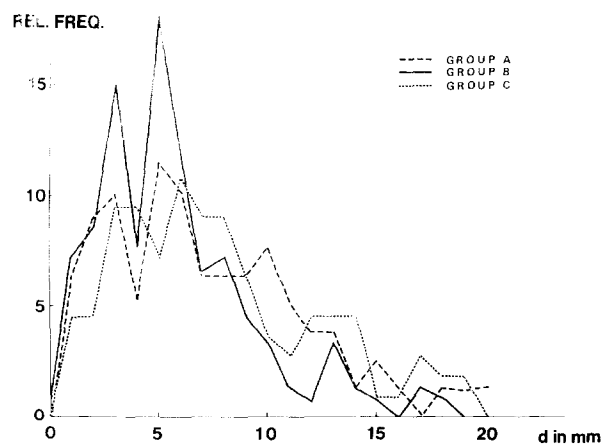The resulting values for s_{xy} are shown in Fig. 7, *b*

Fig. 6. Distribution of d for Group A, B, and C, illustrating the similarity in the shape of the distribution.

Table II. Standard deviation of the X and Y values (S_x and S_y) for the different regions of the maxilla and mandible

Area	S_x	S_y	Significant difference between S_x and S_y
Maxilla			
M	6.3	5.4	no
P	4.6	4.5	no
C	2.6	4.0	yes
1	3.1	4.5	yes
Mandible			
M	3.8	4.1	no
P	4.1	4.3	no
C	2.3	4.5	yes
1	2.1	4.7	yes

$n_x = n_y = 80.$ $F_{0.95} = 1.60.$

which illustrates that very little difference is found in the combined estimate of S between the students making films on a phantom (Group A) and on each other (Group B). It can also be observed that the largest value for the spread was always found in the maxillary molar region.

Theoretically, the differences between the anatomic regions would suggest the use of different field sizes (Fig. 7). Since the maxillary molar region requires the largest field size, this region was selected to determine the optimum field size for using film size 2. The mandibular anterior region was chosen to be representative for exposures using film size 1. The following results, therefore, include exposure of only the maxillary molar and mandibular anterior regions.

Table III.

	□	Δ	▯
Film size 1	$4.7 \times \dfrac{20}{23}$	$4.6 \times \dfrac{20}{23}$	$4.3 \times \dfrac{30}{40}$
	4.1	**4.0**	**3.2**
Film size 2	$5.2 \times \dfrac{20}{25}$	$5.1 \times \dfrac{20}{2\ 5}$	$4.9 \times \dfrac{30}{40}$
	4.2	**4.1**	**3.7**

The optimum field sizes at the tube or cone end were calculated for the maxillary molar region (film size 2) and the mandibular anterior region (film size 1) using the following formula:

$$t = a \frac{b}{c} \text{ (small figures in the table).}$$

a = Field diameter at the film site.
b = Distance from the focal spot to the tube or cone end.
c = Distance from the focal spot to the film.
d = Diameter of the field size at the tube end.

The effect of using different beam-alignment procedures

The ability of the operator to align the cone to the film properly was observed to improve with experience. The most notable improvements occurred within the first six to seven exposures. The influence of the beam-alignment procedures was therefore limited to results obtained from the last three exercises listed in Table I. The rank-sign test was used for comparing the values of d from Groups C and F. This test demonstrated that alignment of the long tube in conjunction with the use of an intraoral film holder and beam-alignment device is significantly more accurate than the other two systems evaluated. No significant difference could be detected between the operator's ability to align the short cone and the short tube.

The influence of experience on the accuracy of beam to film alignment

The ability of the operator to align cone and film accurately was evaluated by determining the percentage of radiographs in which the distance (d) was smaller than 11.5 mm.; the results for the three alignment procedures tested are shown graphically in Fig. 9 and demonstrate clearly the improvement gained with experience. The most significant improvement occurred within the first five exercises. During the first exercises, beam alignment with the use of a cylinder was less accurate than that with the use of a pointed cone, but after 6 or 7 exercises the results were similar. Beam alignment using an extraoral alignment device produced results that were superior to other techniques and required less experience.
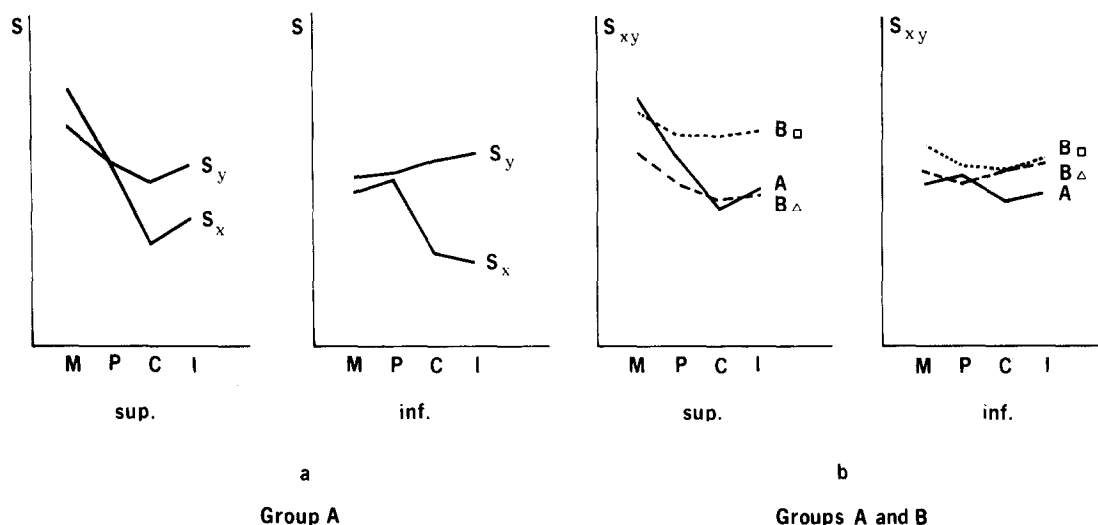
Fig. 7. a, Standard deviation of the X and Y values (S_x and S_y) for different areas of the maxilla and mandible (group A). b, Combined estimate of the spread (S_{xy}) for the different areas of the maxilla and mandible for Groups A and B using the pointed cone and Group C using the short tube.
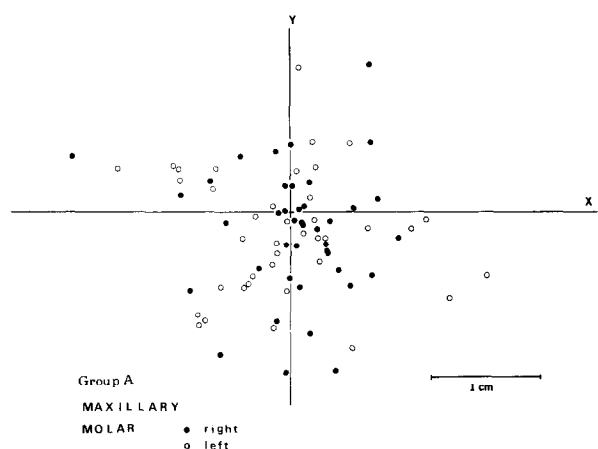

Fig. 8A. Distribution of the points of impact for the maxillary molar region (Group A) (the maximum spread).

The optimum field diameter

Fig. 10 depicts the point of impact (dots 1-6) on a film for various field sizes (circles 1-6) which would not produce cone cutting. The path traced by various possible cone positions and their points of impact delineates an area that is not circular, as may have been expected, but rhomboid. This path varies in size and shape, depending on the field diameter and film size. The percentage of cases in which the point of impact would be directed outside this area gives the percentage of cone cutting. As previously discussed, cone cutting of less than 2 mm. was considered acceptable. With regard to the rhomboid-shaped
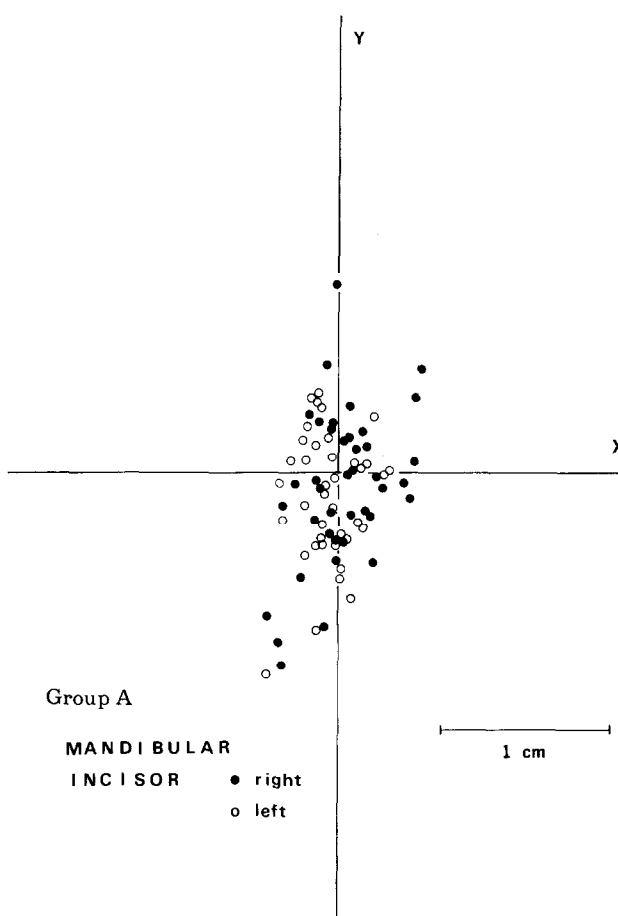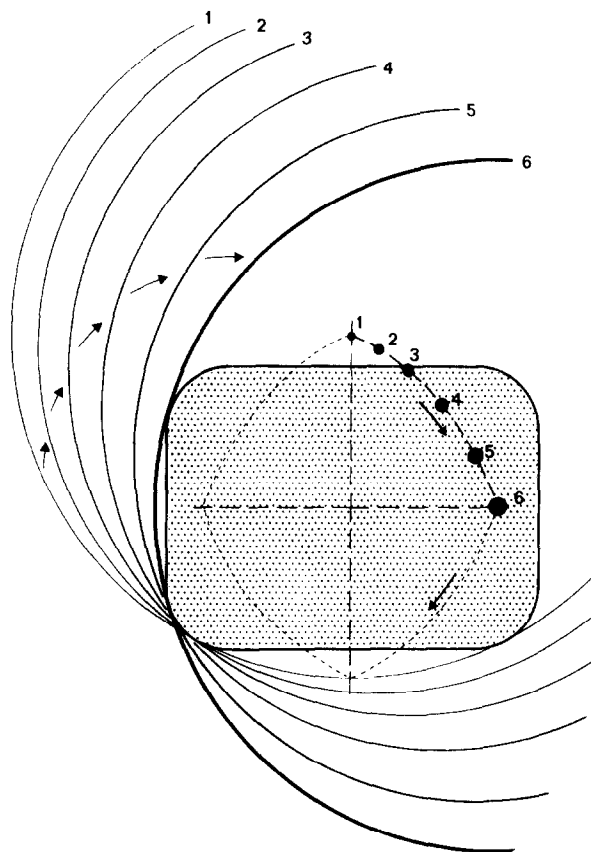

Fig. 8B. Distribution of points of impact for the mandibular anterior region (group A). The minimum spread for X and the largest difference between S_x and S_y were observed in this region.

Exercise no.

0 < d < 11.5 mm
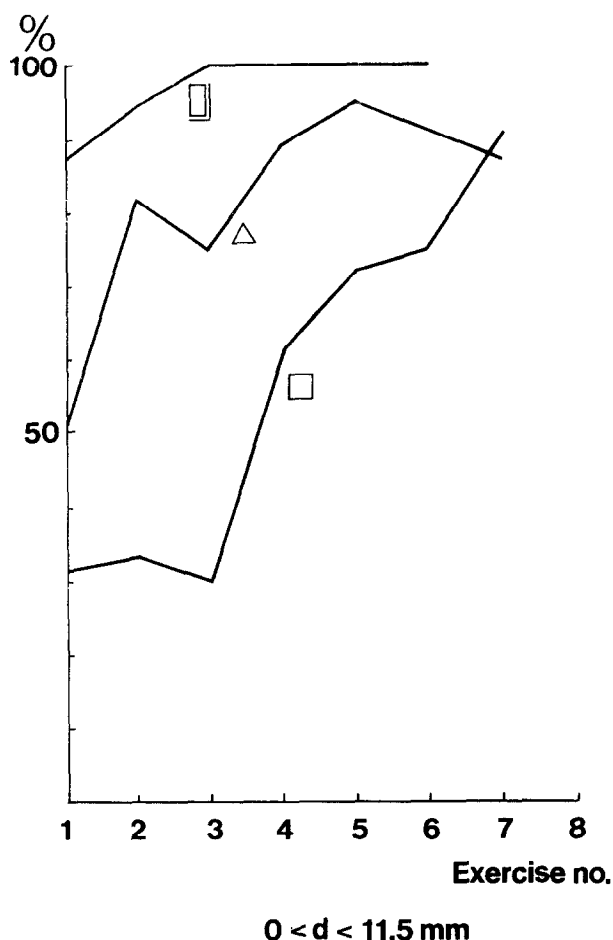
Fig. 9. Percentage of alignments in which d was smaller than 11.5 mm. as a function of experience (exercise number). For identification of the symbols used in the figure, see Table I.

Fig. 10. The area (inside dotted lines) on an x-ray film where the beam axis of a field of the indicated size may intersect the film without producing cone cutting; should the beam axis fall outside this area, cone cutting will occur.

area illustrated in Fig. 10, this means that the outline of the film can be reduced by 2 mm. prior to construction of this rhomboid-shaped area.

The percentage of retakes due to cone cutting taken by operators using various field sizes to irradiate film sizes 1 and 2 is indicated by heavy lines in Figs. 11 and 12. Fig. 11 illustrates the percentage of retakes and the resulting average irradiated area for the maxillary molar region when film size 2 is used. The three curves represent the results for the long cylinder using an alignment device (rectangle), the pointed cone (triangular), and the short cylinder (square); the optimum field diameters were 4.9 cm., 5.1 cm., and 5.2 cm., respectively. The same approach was used for the anterior region using film size 1, with the three curves giving optimum field diameters of 4.3 cm., 4.6 cm., and 4.7 cm. for the three alignment methods. The data suggest that the optimum field diameter should be changed when different regions and/or beam-alignment methods are used and that optimum field diameter will vary between 4.3 cm. and 5.2 cm. It is interesting to note that the previously established arbitrarily defined maximum acceptable percentage of retakes (20 percent) was never used to determine the optimum field diameter.

Because of the divergence of the beam, the field at the end of the tube or pointed cone can be slightly smaller than the optimum diameter; therefore, the field diameter at the end of the tube or cone was calculated with the use of some practical values for the distance between the focal spot and the tube end and the distance between the tube end and the film (Table III). After allowing for beam divergence, it is clear that the field diameter will vary between 3.2 cm. and 4.2 cm.; however, in cases involving exceptionally short distances between tube end and the film, the field diameter should be somewhat larger. For practical reasons, it is appropriate to select one field diameter for all clinical radiographic situations,
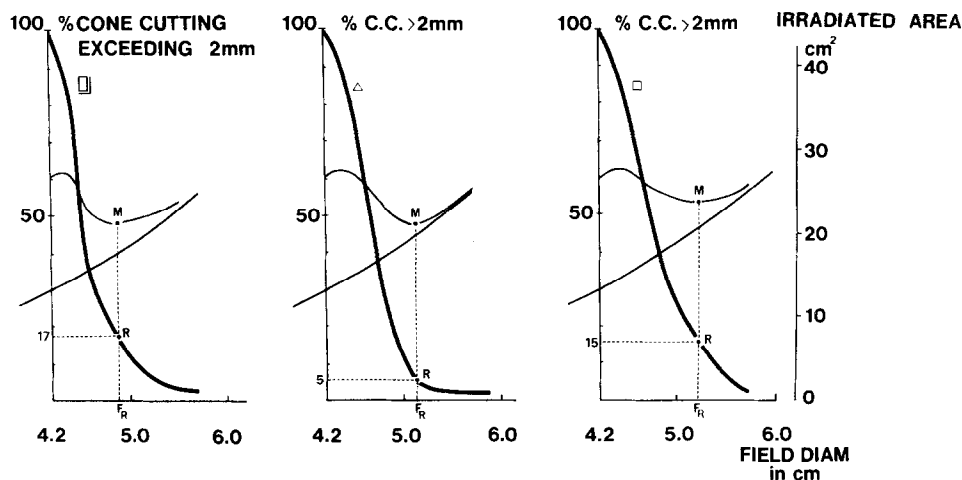
Fig. 11. Graphs indicating the optimum field diameter (F_R) for the three alignment methods using film size 2.
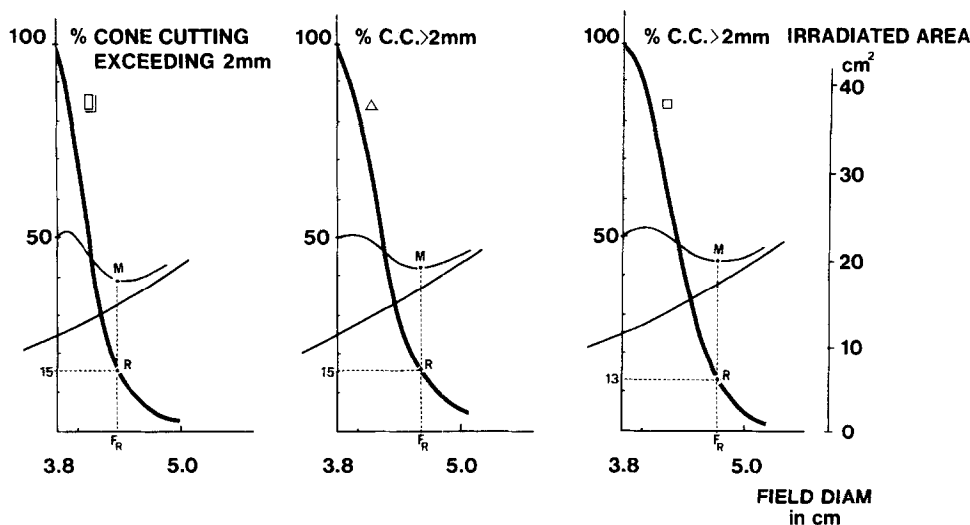
Fig. 12. Graphs indicating the optimum field diameter (F_R) for the three alignment methods using film size 1.

and 4.5 cm. at the tube end satisfies all requirements.

DISCUSSION

The optimum field size for radiographs using film size 2 was derived from alignment results in the maxillary molar region. For the other anatomic sites where beam alignment is easier, the optimum field sizes would be smaller (Fig. 7); consequently, the field sizes listed in Table III would produce a smaller percentage of retakes in other regions of the mouth. When one is determining the diameter of the diaphragm, it should be realized that the focal spot–film distance may vary in different regions of the mouth;

however, a fixed distance is used for techniques using beam-aligning devices. These various distances influence the diameter of the diaphragm needed to produce the required optimum field size at the film site. A theoretically better solution would be to design a variable diaphragm in order to produce different field sizes for radiographing different areas and film sizes. This can be accomplished by means of a diaphragm that can be shifted within the position-indicating device. A prototype of a device enabling the operator to change the diameter of the field size at the tube end from 3 cm. to 7 cm. is shown in Fig. 13.

Cone cutting exceeding 2 mm. was considered
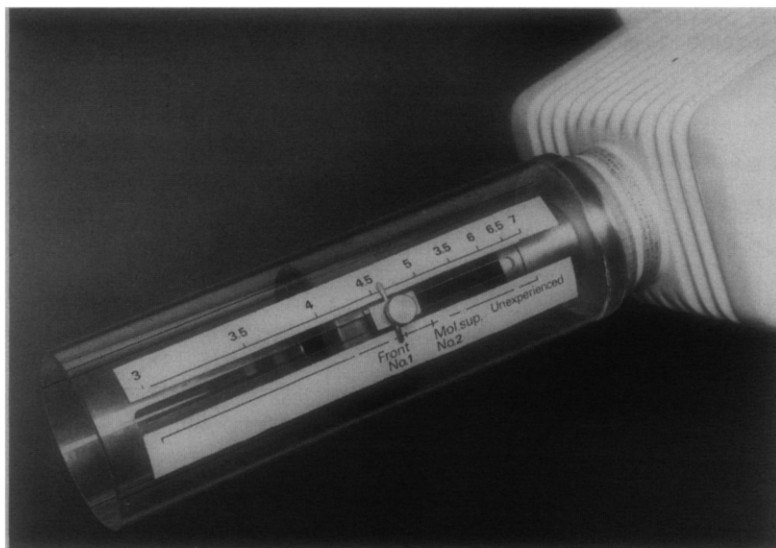
Fig. 13. A prototype long tube with a movable diaphragm that can be shifted to produce a continuously variable field size at the end of the tube from 3 cm. to 7 cm. in diameter.

unacceptable and required a retake. If a larger section of a corner of the film is cone cut, a practitioner will generally not make a retake when the object of interest is located elsewhere on the film or the area of interest is visible on other radiographs within the complete-mouth radiographic survey. In practice, this means that the percentage of retakes may be smaller than the percentages found for the optimum field sizes. The occasional occurrence of cone cutting can be considered as a proof of a maximum effort to reduce irradiation of the patient. In other words, if the field size is reduced to the minimum, then occasional cone cutting will occur; if the field size is too large, cone cutting will seldom occur.

SUMMARY

1. In clinical dentistry, because of the increased probability of retakes, a smaller x-ray beam is not necessarily associated with less irradiation of a patient. In view of certain premises, these two variables can be used to determine an optimum field diameter. The use of the minimum average field diameter to irradiate a patient is not necessarily associated with the smallest number of retakes.

2. Basically, this optimum field diameter can be associated with an unacceptable percentage of retakes. In this study, however, there was no need to use the established maximum acceptable percentage of retakes (20 percent) to determine this optimum field diameter.

3. Clinically, the choice of an optimum field diameter depends also on defining the maximum amount of "acceptable" cone cutting before a retake is required; 2 mm. was established as the limit in this study.

4. The ability of an operator to align the tube/cone and film accurately is considerably improved after four to seven sessions. The amount of practice required to produce comparable accuracy in the alignment of tube and film was smallest when the long tube and alignment device were used, higher for the short cone, and highest for the short tube.

5. The optimum field diameter for various beam alignment methods and film sizes is given in Table II.

6. The best compromise if one field diameter has to be selected is 4.5 cm. at the tube end.

CONCLUSION

At present the I.C.R.P. recommends a diameter of 6 cm. but will accept a maximum of 7.5 cm. On the basis of the data presented, these recommendations appear to be too liberal. The beam diameter recommended from this investigation (4.5 cm.) would irradiate 44 percent less area than a 6 cm. diameter field and 64 percent less than a 7.5 cm. diameter field.

APPENDIX

It was assumed that the coordinates of the points of impact were independent normal random variables with the same standard deviation. With these assumptions, it can be concluded that

$$\frac{d^2}{\sigma^2}$$

is χ^2 distributed with 2 degrees of freedom. An estimate of σ^2 can be made by calculating

$$\frac{\Sigma \, d_i^2}{2 \, n}.$$

The distribution of d was tested for goodness of fit to a χ^2 distribution. The test gives a significant result. Fig. 5, *c* presents the distribution recorded and the theoretical χ^2 curve. When d is χ^2 distributed, the probability that d will exceed a certain value (that is, the probability of cone cutting when the area on which the beam axis may be directed without producing cone cutting is assumed to be a circle) is normally distributed. This distribution has a variance σ^2, which is equivalent to the combined variance of the X and Y coordinates of the points of intersection.

Because of the significant deviation from a χ^2 distribution, the conclusions in the different sections are based on the real distribution as found in the experiments (except for Table II and Fig. 7).

The following remark has to be made concerning the application of the F test in Table II: For this test based on normal distributions, a small error[3] could be accepted because the distribution is bell shaped with one peak at the average and the samples are relatively large (n = 780).

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