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EFFECT OF ANATOMICAL IRREGULARITIES ON THE DOSE IN ELECTRON BEAM THERAPY

by

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Although high-energy electrons have been used in therapy for many years, little still seems to be known regarding the effect of irregularities of human anatomy on the dose distribution. When such irregularities are due to bodies of limited width, then perturbations of the normal dose distribution, as seen in homogeneous tissue, may cause either small areas of overdose (hot spots) or areas of underdose (cold areas). The former may be large enough to damage vital organs or to develop necroses; the latter may allow tumour cells to survive treatment and thus lead to recurrence. These assumptions have constantly worried therapeutists and physicists. To calculate the effect of irregularities by theoretical means seems a tedious approach, the effect being dependent on the geometrical dimensions of the perturbing structures. The application of the Monte Carlo technique would be a time-consuming task even for a single case. The present experimental approach is comparable to the investigations of BREITLING & VOGEL (1963) and NETTELAND (1965) but has been accomplished in a way to facilitate the understanding of the effect of irregularities in clinical practice. A comparison with the corresponding changes in cobalt therapy has been made.

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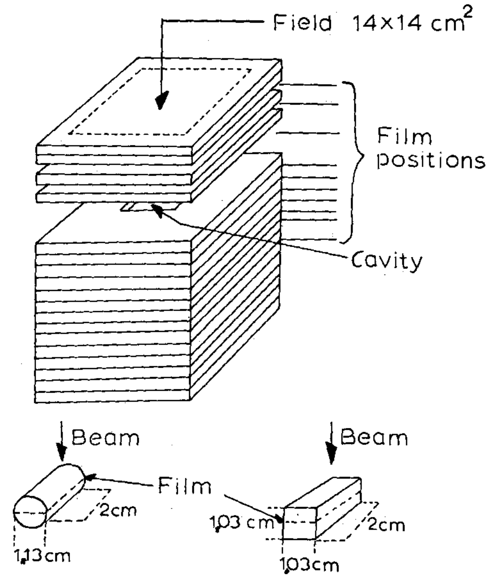


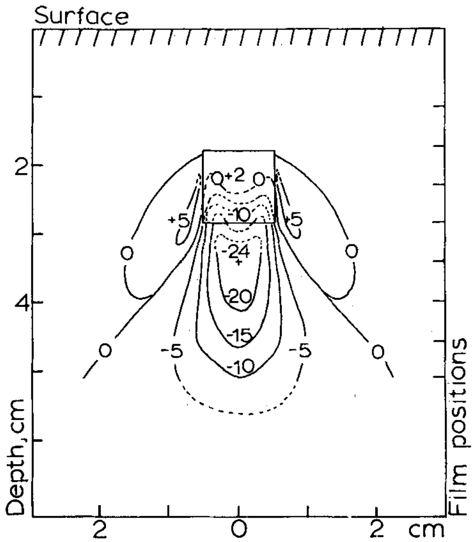
Fig. 1. Polystyrene phantom with a cavity for perturbing bodies (top), and the perturbing bodies introduced in the phantom.

Effects of dense structures. The dose was measured by means of Kodak M radiographic film. This film has a linear density dose response, especially when it is exposed perpendicular to the emulsion plane, which direction was also considered the optimal one for reducing perturbation of the dose distribution from the film itself.

Perturbation of the dose distribution was studied in homogeneous, nearly water-equivalent, tissue. The results were made applicable to dose planning by expressing the perturbation in percent of the unperturbed dose at dose maximum. The dose distribution was studied in planes perpendicular to the electron beam at several depths, the films being measured by means of a Joyce double-beam micro-densitometer. The deviations of the perturbed densitograms from the unperturbed ones were then plotted, as illustrated in Figs 2 to 5.

The films were irradiated in a phantom (Fig. 1) placed between polystyrene slabs with a density, ϱ, of 1.04 g/cm^3 and an effective density, ϱ_{eff}, of 0.97 (Loevinger, Karzmark & Weissbluth 1961). A comparison with the corresponding value for perspex (lucite), 1.12, indicates a better equivalency with water.

The perturbing bodies in the soft-tissue material (Fig. 1) consisted of bone powder or lead. The bone powder was obtained by milling cattle bones, cooking the powder in water, and drying. The powder was then pressed in steel moulds under high pressure, using a small amount of cellulose lack as binding agent.



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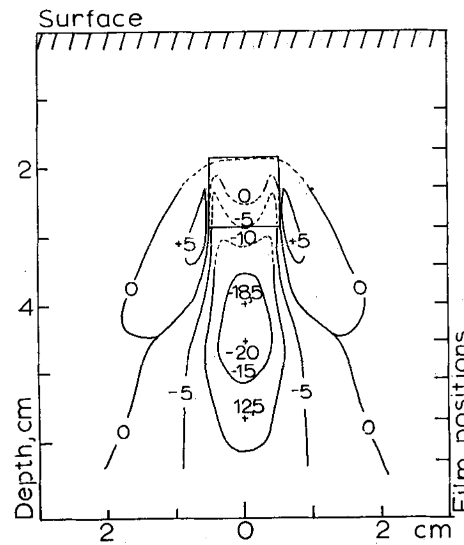

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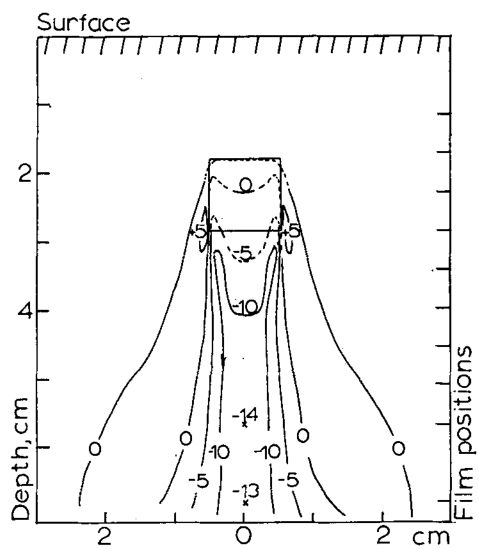

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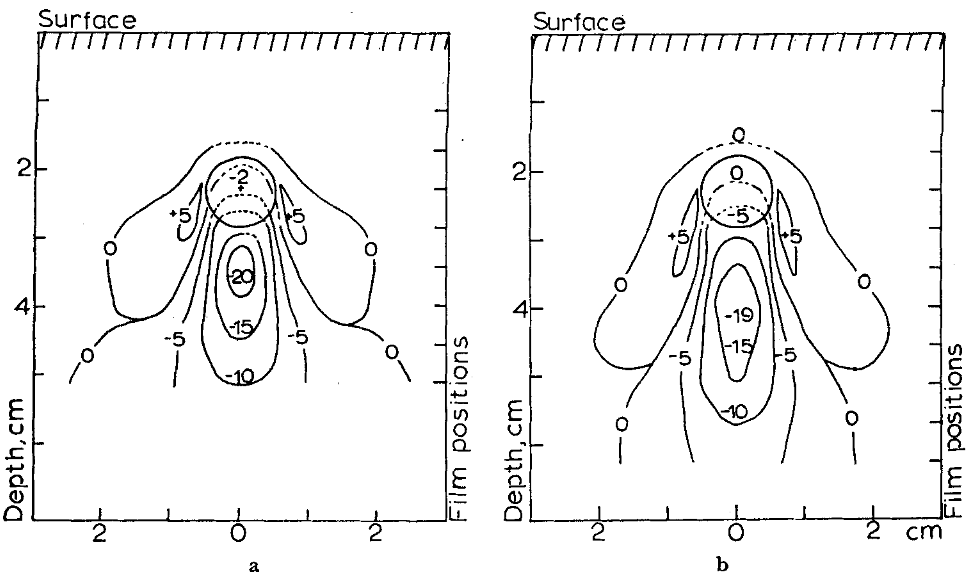
Fig. 2. Perturbation in dose distribution caused by a bone prism of size 1.03 cm × 1.03 cm × 2 cm in percent of the maximum dose at the respective energies of 15 MeV (a), 20 MeV (b) and 34 MeV (c).

The resulting density was 1.54 kg/cm^3. Bones are actually not homogeneous, and for comparison it may be mentioned that the density of the mandible may be of the order of 1.65 g/cm^3 (HAAS & SANDBERG 1957).

The perturbation caused by a bone prism of size 1.03 cm by 1.03 cm by 2 cm at primary energies of, respectively, 15 MeV, 20 MeV, and 34 MeV is indicated in



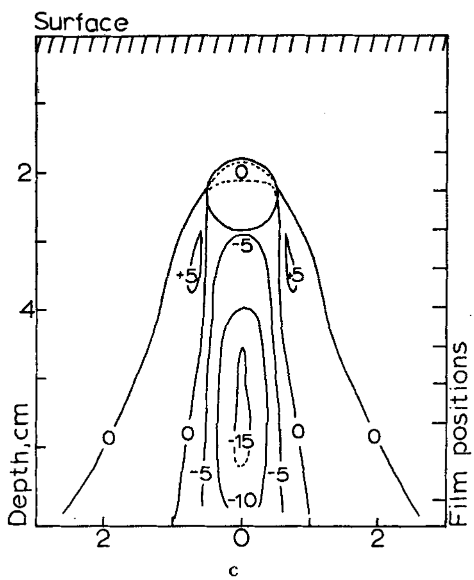
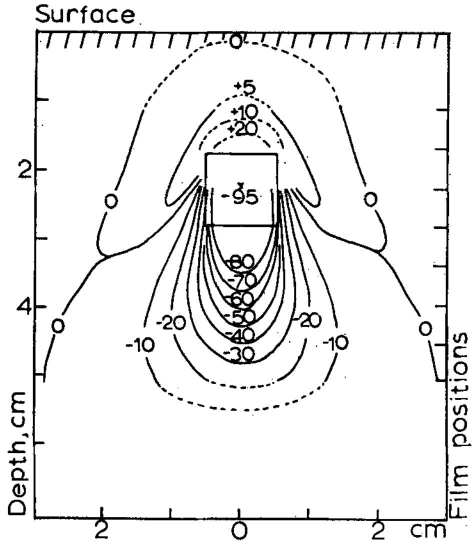


Fig. 3. Perturbation caused by a bone cylinder in percent of the maximum dose at the respective energies of 15 MeV (a), 20 MeV (b) and 34 MeV (c).

Fig. 2. The distribution is given for a plane cutting the prism perpendicularly in two pieces each of the size 1 cm by 1 cm. The influence of the prism seems to result in two areas of perturbation: (1) a 'shadow' area, and (2) a side-scatter area.

The explanation for the appearance of area (1) is simple. The radiation



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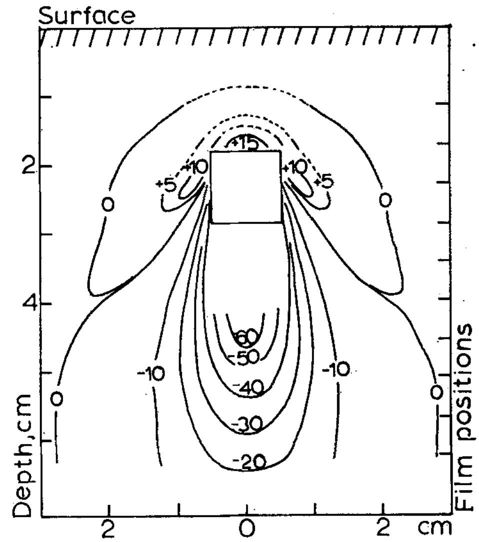

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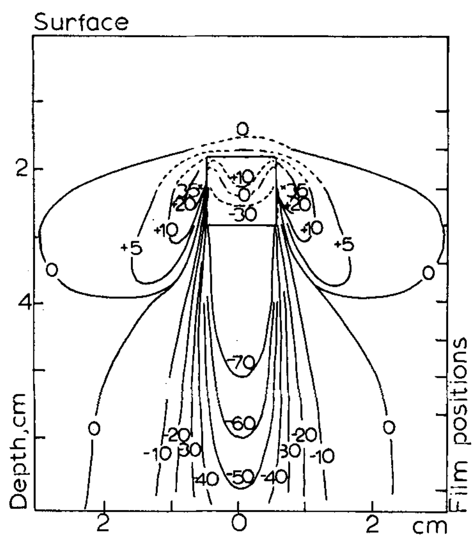

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Fig. 4. Perturbation caused by a lead prism in percent of the maximum dose at, respectively, 15 MeV (a), 20 MeV (b) and 34 MeV (c). The regions between —50 % and —100 % are not completely covered.

entering from the front face of the piece is absorbed (the particles are more or less arrested) in the piece, or scattered from the piece, resulting in a 'shadow' or a 'cold' volume of low dose. The effect is well known in roentgen and cobalt therapy.

As to the second area of perturbation, the radiation scattered from the bone

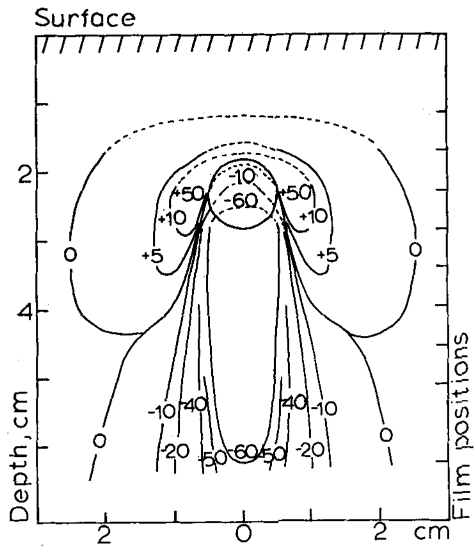


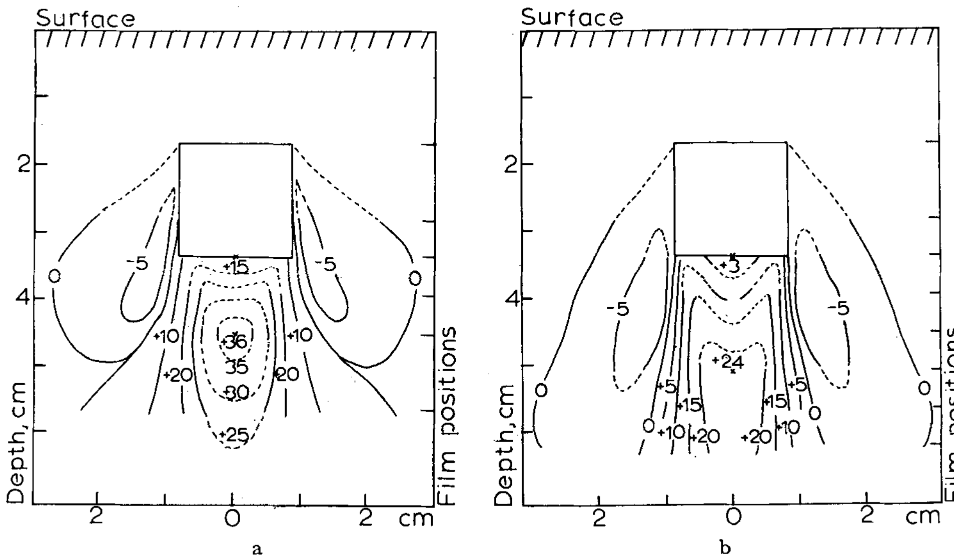
Fig. 5. Perturbation caused by a lead cylinder (cf. fig. 4c).

prism causes an overdose close to the piece. This effect is not so marked with roentgen rays and cobalt radiation but in the case of electrons should be considered as a new phenomenon to be taken into account.

The overdose value does not change with energy, being always between 5 % and 10 %. The underdose, on the contrary, varies between — 20 % and — 14 % when the energy is increased from 15 to 34 MeV. With increasing energy, the position of the point of lowest dose moves farther from the piece. The volume covered by the 'shadow' reaches far behind the piece at 34 MeV but is shortened at lower energies. The underdose becomes more evident at lower energies.

The perturbation caused by a cylinder of the same material, volume and cross-section as the prism was studied in a corresponding manner. The result is recorded in Fig. 3. Excepting error of measurement, the perturbation may be considered to amount to the same value as for the prism, the only significant difference being the shapes of the isodoses close to the piece.

The dose distribution with a lead prism is given in Fig. 4. The electrons do not penetrate the piece at all. The underdose behind the prism is thus approximately 100 % at 15 MeV, 20 MeV, and 34 MeV. Pure scattering from the soft medium is clearly demonstrated and stands for the dose in the 'shadow', i.e. for the difference between the percentage read in the 'shadow' and 100 % perturbation. The effect of bremsstrahlung from the piece and the machine should be considered, however, if an exact estimate of the pure scattering effect is to be made. The hot spots beside the lead represent a 35 % overdose as com-



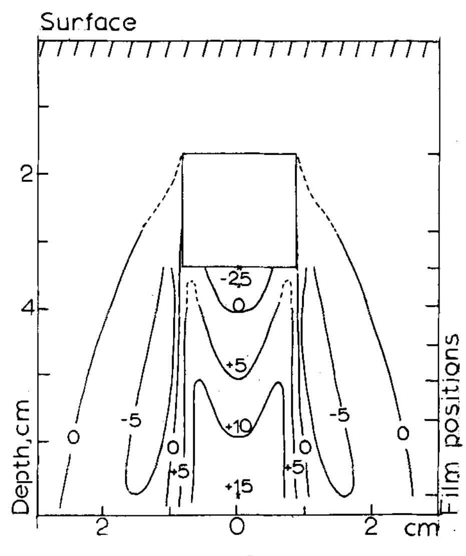


Fig. 6. Perturbation caused by an air cavity in percent of the maximum dose at, respectively, 15 MeV (a), 20 MeV (b) and 34 MeV (c).

pared to only 5 % with bone. Moreover, the effect of backscattering is considerable, at least at low energies. The geometrical shape may be of some slight influence when the perturbing body is lead (Fig. 5).

Effect of cavities. Situations of a cavity perturbing the dose distribution may frequently arise in radiation therapy. To simulate the trachea, a cavity shaped

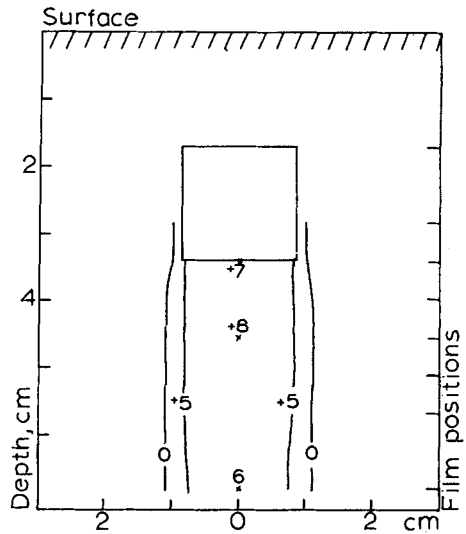


Fig. 7. Perturbation at cobalt radiation caused by an air cavity in percent of the maximum dose (cf. fig. 6).

as a long channel of 2 cm by 2 cm cross-section was introduced in a polystyrene phantom. Exposure to electrons was performed as previously. The phantom was also exposed to a cobalt beam, to provide a comparison between electron and cobalt beam therapy. The density was measured by an Ansco Macbeth densitometer. The result is illustrated in Fig. 6. The perturbation in the two areas is now inverse, compared to the previously investigated conditions. There is now a 'positive shadow' (overdose) due to the absence of absorption in the cavity. The absence of scattering normally produced by soft tissue (now removed) causes an underdose beside the cavity.

No scatter effect at all could be observed with cobalt radiation (Fig. 7). The 'positive shadow' is moreover far less marked than that produced by the electrons. Its highest isodose is + 35 % at 15 MeV electrons and decreases to + 15 % at 34 MeV. The highest value for cobalt is + 8 %.

Discussion

Let us now consider the perturbation occurring in the two main cases discussed. There are as mentioned two different areas of deviation with different signs. These are (1) the shadow that is 'negative' in the first case (underdose) and 'positive' in the second (overdose) and (2) the 'side scattering area' characterized by an overdose in the first and an underdose in the second case.

The boundaries of the piece of bone or the cavity define a certain domain in the soft tissue-equivalent material. It may now be useful to consider the dose as

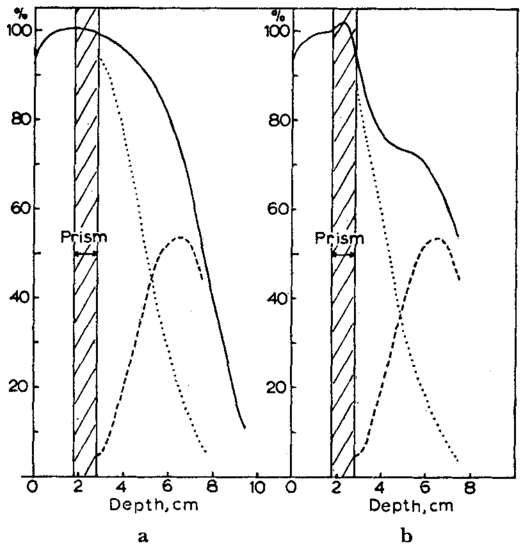


Fig. 8. Curves showing the total dose of 20 MeV electrons (solid), unperturbed partial dose (dashed), and zero-perturbed or perturbed dose (dotted) at different depths along the centre line through the domain (a) in a homogeneous phantom and (b) when the domain is filled with the bone prism.

caused by two different groups of electrons. One group is made up by perturbed electrons, i.e. by primary or secondary electrons having penetrated the perturbing domain or by electrons struck directly or indirectly by them. The energy and direction of the perturbed electrons are related to the type of matter (or void) introduced in the domain. The other group is represented by electrons not having penetrated the domain and not being secondaries of a first or higher generation to perturbed electrons; this group may be called unperturbed electrons. The total dose can accordingly be divided into two parts, the perturbed and the unperturbed partial dose.

The results obtained for lead (Fig. 4) enable a study to be made of the unperturbed partial dose, at least in the 'shadow' area reached by the unperturbed electrons by scatter from tissue-equivalent material surrounding the domain. It may be assumed that only a negligible amount of electrons entering the domain will penetrate parts of the lead piece and scatter to the area behind the domain. Using a common depth dose curve for 20 MeV, and the results of Fig. 4b, we obtain the curves in Fig. 8a which apply to a homogeneous case. The solid curve gives the total dose and the dashed curve the unperturbed dose according to Fig. 4b. The difference between these two curves (shown dotted) represents the dose due to 'zero-perturbed electrons', or that part of the dose which will be affected when the tissue-equivalent material that now fills the domain is replaced by matter of different electron density or void. It should be pointed out that the curves of Fig. 8 are related to a domain with the special shape of the prism illustrated in Fig. 1. Another domain would give curves of different shapes.

The dotted curve may be considered a depth dose curve for those electrons that have been influenced by the matter in the domain. If matter with a high electron density is introduced, two main effects result. The energy of the zero-perturbed electrons is reduced, and the scattering is increased to give an ensemble of perturbed electrons. The first effect will reduce the range of the curve, and the second will reduce the slope of the curve. The combined effect is seen in Fig. 8b, where the solid line gives the depth dose curve through the bone prism according to Fig. 2b, and the dashed line is the same as in Fig. 8a. The dotted curve again represents the difference or the dose due to the electrons perturbed by the bone prism. The most prominent perturbation of the dose is expected in a region where the zeroperturbed partial dose curve has a steep slope. This is illustrated in Fig. 8. The increase in the distance between the domain and the position of maximum perturbation with increasing energy is therefore understandable.

The perturbation in the shadow area is high enough to be of importance in dose planning. This applies to solid bone as well as to cavities. A calculation of the perturbation is complicated by two facts. First, only a part of the electrons forming the dose is perturbed, as seen above; secondly the depth dose curves of the perturbed electrons depend strongly on the size of the perturbing piece. It is evident that the perturbation on the whole does not depend only on the thickness of the domain but also on its width, which defines the ratio of perturbed and unperturbed electrons. How complicated the situation may be when planning treatments of the head is obvious. Nearly all the electrons are more or less perturbed in some areas when passing bone and cavities of varying thickness and shape. It may however be possible to find approximate methods to calculate the dose in areas of such complex structure (LAUGHLIN 1966).

The present results indicate that the maximum value of perturbation decreases with increasing energy. This is true for bone and air cavities. At lower energies the mean scattering angle is larger, facilitating the scattering of unperturbed electrons on to the shadow area; this is expected to increase the relative importance of the unperturbed electrons in forming the dose at the cost of the contribution of perturbed electrons. At lower energies, however, the change in the depth dose curve for the zero-perturbed group by the introduction of perturbing matter (or void) will influence an area that lies closer to the domain than the region reached by the bulk of unperturbed electrons. The perturbed electrons in this area will dominate the dose to give the more marked perturbation observed at lower energies.

The results clearly indicate that the perturbation at the side area is of minor importance. Care should be taken to remember the overdose of 5 % near bone and the underdose of 5 % near a cavity (Figs 2, 3 and 6). If lead is to be used as a shield surrounded by tissue, the strong side-scattering effect should also be born in mind. The back-scatter in lead is considerable but negligible in bone.

It should be mentioned that the perturbation at an air cavity gives, when taken with an opposite sign, the amount of side-scattered electrons from the domain when filled with tissue-equivalent material.

It is interesting to consider that the perturbation of the cobalt radiation by a cavity (Fig. 7) is much smaller than the perturbation of electrons. The same results is expected when bone is used as perturbing body.

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SUMMARY

The effect of bone and cavities on the dose distribution of electrons was studied on radiographic film at 15, 20 and 34 MeV. Bone and lead pieces of two different shapes, and a cavity surrounded by polystyrene, were used to simulate anatomical irregularities. The results were compared with similar measurements for cobalt radiation, and the perturbation for electrons was found to be much greater than for cobalt.

ZUSAMMENFASSUNG

Der Einfluss von Knochen und Hohlräumen auf die Dosisverteilung bei Elektronenbestrahlung bei 15, 20 und 34 MeV wurde mittels Röntgenfilm studiert und gemessen. Knochen und Bleistücke von zwei verschiedenen Formen und eine von Polystyren umgegebenen Höhle wurden verwendet um anatomische Irregularitäten darzustellen. Die Resultate wurden mit den Messresultaten bei Kobaltbestrahlung verglichen und es wurde festgestellt, dass die Störung bei Elektronenbestrahlung grösser als bei Kobaltbestrahlung war.

RÉSUMÉ

L'effet des os et des cavités sur la distribution de dose d'électrons a été étudié à 15, 20 et 34 MeV au moyen de films radiographiques, avec des morceaux d'os et de plomb de deux formes différentes et avec une cavité entourée de polystyrène pour simuler les irrégularités anatomiques. Les résultats sont comparés avec ceux de mesures semblables faites pour le rayonnement du cobalt. La perturbation de la distribution de dose est bien plus importante pour les électrons que pour le cobalt.

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