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CALCULATION OF RADIOACTIVE IODINE BETA RADIATION DOSE TO THE BONE MARROW

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When doses of ^{131}I of the order of 100 mc or more are administered, as is sometimes done in the treatment of thyroid carcinoma, the associated irradiation of the hematopoietic tissues is the most important factor limiting the dose which the patient can tolerate. The radiation delivered to the bone marrow is usually estimated by assuming that the dose of radiation delivered to the bone marrow is equal to that delivered to the blood (Rall, Foster, Robbins, Lazerson, Farr and Rawson, 1953; Seidlin, Yalow and Siegel, 1952; Marinelli and Hill, 1950), the method of Marinelli, Quimby and Hine (1948) being used to calculate the dose delivered to the blood. This method includes the assumption that for the β-particle contribution to the dose the energy released and the energy absorbed in a unit volume of a given tissue are equal. Although the hematopoietic portion of the bone marrow is a soft tissue, the tissue regarded anatomically as the bone marrow is characterised by the presence of interspersed bony trabeculae which absorb some of the energy released in the soft tissue. Therefore, the assumptions involved in the soft-tissue method of dose calculation are not strictly valid for bone marrow. An estimate of the energy absorbed in the bony trabeculae is derived in the present article.

A major requirement in establishing the required estimate is a value for the relative volume of the marrow occupied by bony trabeculae. This part of the problem was approached by measuring the bony areas of representative portions of normal appearing marrow from ribs and vertebrae obtained routinely at autopsy from adult patients dying of various diseases.* Sections were stained with haematoxylin and eosin. Photomicrographs of one or more fields from each of the several bone sections were made on 4×5 in. Ektachrome film at low-power magnification. An effort was made to select representative fields with average distributions of trabeculae and marrow. The area occupied by the bony trabeculae was obtained by planimetry. It is apparent that any figure so obtained for the trabecular area must be regarded as an approximation only, because the structure and composition of bone varies among individuals with their age, health and nutritional status and in a given individual there are variations from bone to bone and even from point to point in the same bone.

The areas obtained in measurements made in twelve selected fields were: 19·4, 18·4, 17·2, 16·4, 15·8, 9·9, 9·2, 8·8, 8·0, 6·7, 5·1 and 4·0 per cent of the area of the field. The mean for this series is 11·6 per cent. It is not areas, however, but volumes which are significant in determining radiation absorption. It is easily shown that the relative areas represent the relative volumes. As a first approximation we shall assume that the orientation of the trabeculae is random. Consider a block of unit height and width having its contents distributed in two phases with the fraction, f^2, of its volume in phase II as illustrated in Fig. 1. A section through

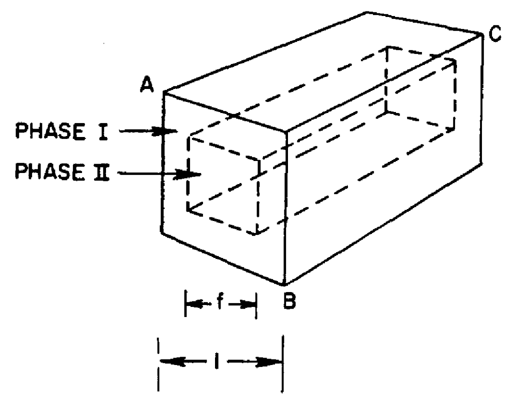

Fig. 1.

this block parallel to face AB has the fraction, f^2, of its area in phase II. Of the sections parallel to face AC or to BC, a portion $(1-f)$ will have none of their areas in phase II, while those in the remaining portion, f, will have f of their areas in phase II, so the average area for these sections is also f^2. For other orientations of sections the averaging effect may not be so obvious, but since the sums of the areas multiplied by the thicknesses of the sections gives the volumes involved, for uniformly thin sections the average percentage area of phase II represents the percentage volume of phase II.

* Dr. Henry L. Jaffe kindly supplied several of the bone sections used in this study.

The next factor to be considered is the density of the bony trabeculae. These are here assumed to have the same composition as that reported for compact bone (Koch, 1917; Mack, Brown and Trapp, 1949; Strobino and Farr, 1949). Compact bone is about 70 per cent ash and the ash is chiefly $Ca_3(PO_4)_2$. Koch's (1917) values for the specific gravity of compact bone average 1·955, and he quotes other studies giving results in the same range.

The rate of energy loss per unit of path length for β particles depends upon the velocity of the particle and upon the electron density of the absorbing medium. In practice, the range of β particles is expressed in units of areal density, mg/cm². Decay of ^{131}I occurs through the emission of one of four β particles followed by a variety of γ rays (Bell and Graham, 1952). In 87·2 per cent of the disintegrations the β has a maximum energy of 0·608 MeV. The balance of the disintegrations involve maximum β energies of 0·812, 0·335 and 0·250 MeV. The average energy for ^{131}I β particles is about 0·200 MeV (Marinelli *et al.*, 1948; Rall *et al.*, 1953).

In water, the range of the 0·608 MeV particles is about 200 mg/cm² (Glendennin, 1948), or about 2 mm, while the range for particles at the average energy is about 0·4 mm. The corresponding ranges in bone of density 2·0 are 1 and 0·2 mm. Representative thicknesses of the trabeculae in the fields studied ranged from 0·04 to 0·25 mm, while representative distances between trabeculae ranged from 0·20 to 0·70 mm, so that the paths of most of the β particles are partly in bone. An exact estimate of the proportion of energy absorbed in bone would involve a very complicated analysis of the geometry involved, but for present purposes it may be assumed that the division of energy absorption between bone and soft tissue in the marrow is proportional to the products of the volumes and densities of the two phases.

If the bony trabeculae occupy 12 per cent of the marrow volume as found above, and if the bone density is taken as 2·0, 21·4 per cent of the mass of the material in the marrow is bone and about 21 per cent of the β energy will be absorbed in bone according to the above assumptions. This means that the radiation dose which affects the soft tissues in the marrow is about 79 per cent of the dose calculated for blood if the concentration of radioactive iodine in the marrow is equal to that in the blood. This figure is strongly dependent upon the value used for the relative volume of the trabeculae in the marrow.

Some of the discrepancies which appear in the response of the hematopoietic tissues to large doses of ^{131}I and other agents may be explained by the absorption of some of the β energy in bone. Bloom (1948, p. 14) reports that for mice the LD_{50}/30 days for ^{24}Na was found to be 30 μc per g, which corresponds to a β-radiation dose of 810 rep., whereas the LD_{50}/30 days with X rays on mice was about 530 r. The calculations for many other agents are complicated by peculiarities of their concentration in bone. For the very weak β emitters, in particular tritium, the range in the marrow is so short that relatively little energy is lost by absorption in bone.

Only the β contributions to the dose have been considered in the above discussion. The γ contribution may be important too, and may be especially high if there are iodine-concentrating metastases in or near the hematopoietic tissues (Rall *et al.*, 1953).

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SUMMARY

1. The area occupied by bony trabeculae in representative fields of the bone marrow from human ribs and vertebrae was found to average 12 per cent of the total area.

2. The fraction of the ^{131}I β-particle energy absorbed by bony trabeculae in the bone marrow is estimated as 20 per cent of the energy released in the marrow.

3. If the concentration of radioactive iodine in bone marrow equals that in the blood, the β-radiation dose delivered to the marrow is about 20 per cent less than the dose delivered to the blood.

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