AECU-2895

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No. 43978

ENERGY ABSORPTION IN BONE

by

Bennie S. Friesen
A.B., University of Kansas, 1952

Submitted to the Committee on Radiation Biophysics and the Faculty of the Graduate School of the University of Kansas in partial fulfillment of the requirements for the degree of Master of Arts.

Instructor in Charge

January, 1954

For the Committee

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UNITED STATES ATOMIC ENERGY COMMISSION

AECU-2895

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April 1955
[TIS Issuance Date]

University of Kansas
Lawrence Kansas

Technical Information Service, Oak Ridge, Tennessee

Subject Category, BIOLOGY.

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ACKNOWLEDGEMENTS

The author wishes to express the deepest appreciation to Dr. Frank E. Hoecker for the counsel, aid and encouragement he faithfully rendered. Acknowledgement is made to Dr. Charles A. Leone for suggestions offered, to Dr. Homer L. Hiebert and Stormont-Vail Hospital, Topeka, Kansas, for making the Maxitron two-fifty available for use, and to Mr. Norman Hoecker for technical aid. This work was partially supported by the A.E.C. under contract No. AT(11-1)-83-II.

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I. INTRODUCTION

The purpose of this investigation was to make an experimental determination of the absolute energy absorption per unit mass in cortical bone under certain specified conditions of irradiation. The correlation of the amount of energy absorbed and the subsequent physiological effects would be of interest to those concerned with radiation therapy.

Only a few investigations have been made of the relationship of energy absorption in bone to the amount and quality of radiation to which it has been subjected. Most of these have been indicative rather than quantitative. Spiers'[1,2] work does represent an experimental quantitative study of the above relationship, but his approach was different from the one employed in the experiments described in this thesis. As a consequence, the assumptions which had to be made in order to make his experimental approach feasible are different from the ones used as a basis for the work presented here. For this reason, comparison of results should be quite instructive. On the other hand, Mayneord[3]

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1 F. W. Spiers, "Effective Atomic Number and Energy Absorption in Tissues," British Journal of Radiology, XIX (1946), 52-62.

2 F. W. Spiers, "Dosage in Irradiated Soft Tissue and Bone," British Journal of Radiology, XXIV (1951), 365-368.

3 W. F. Mayneord, "Secondary Electronic Emission from Metal Foils and Animal Tissues," Proceedings of the Royal Society of London, Series A, CXXX (1930), 63-80.

and Stenstrom[4] used cavity ionization methods in their experimentation, but no attempt was made to make the procedures conform to the limitations which make the results capable of being interpreted in terms of energy absorption. Thus it was felt that the information gained by this investigation should be of value in the field of radiology.

Secondary objectives were the design and construction of an ionization chamber made from cortical bone and the determination of the ratio of the average maximum ranges of electrons of specified energy in two different media.

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II. THEORETICAL BASIS OF THE EXPERIMENT

The utilization of thimble ionization chambers suggested itself as the most direct and convenient method of investigating the stated problem. Bragg[5], Fricke and Glasser[6], and Gray[7,8,9,10] each independently studied cavity ionization methods. The mathematical basis for the use of such chambers as a tool in research has been developed by Gray[11]. He derived a relationship between the ionization per unit volume per unit time in an infinitely small air cavity introduced into a solid medium and the energy absorbed per unit volume per unit time in the same solid medium when it was being irradiated with uniform intensity. This relationship is mathematically stated as follows:

$$E_v = {}_{m}S/{}_{G}S \; J_v \; W \qquad 1)$$

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5 W. H. Bragg, Studies in Radioactivity (1912), pp. 91-99.

6 H. Fricke and O. Glasser, "A Theoretical and Experimental Study of the Small Ionization Chamber," American Journal of Roentgenology, XIII (1925), 453-461.

7 L. H. Gray, "The Absorption of Penetrating Radiation," Proceedings of the Royal Society of London, Series A, CXXII (1928), 647-668.

8 L. H. Gray, "An Ionization Method for the Absolute Measurement of Gamma Ray Energy," Proceedings of the Royal Society of London, Series A, CLVI (1936), 578-596.

9 L. H. Gray, "Radiation Dosimetry, Part I," British Journal of Radiology, X (1937), 600-612.

10 L. H. Gray, "Radiation Dosimetry, Part II," British Journal of Radiology, X (1937), 721-742.

11 L. H. Gray, "An Ionization Method for Absolute Measurement of Gamma Ray Energy," Proceedings of the Royal Society of London, Series A, CLVI (1936), 578-596.

where $_{M}S$ is the stopping power of the medium for electrons, $_{G}S$ is the stopping power of the gas in the cavity for electrons, J_v is the number of ion pairs formed per unit time per unit volume in the gas of the cavity, W is the average energy lost by an electron per pair of ions formed, and E_v is the energy absorbed per unit time per unit volume in the solid medium.

The above relationship is valid only within certain limitations which may be summarized in four statements.

I. The ion chamber (essentially an air cavity in a medium) must be of such material that the ionization per unit volume in the air cavity is proportional to the gas pressure in the cavity.

II. The ionization per unit volume in the air cavity must be independent of the size of that cavity.

III. The primary beam of radiation should not be appreciably attenuated in traversing the chamber.

IV. The walls of the chamber must be thick enough for the primary beam of radiation used to be in radiative equilibrium with the secondary particles produced in the medium.

A bone ion chamber made to conform to the above limitiations could therefore be used to determine the energy absorption in bone when it is irradiated with a given beam of gamma-rays or x-rays.

The above discussion indicates, and experimentation by Gray[12] and Mayneord and Roberts[13] on various materials has shown, that the following result should be obtained if various wall thicknesses of the material surrounding an air cavity were plotted against the ionization per unit time in the cavity when the material is being uniformly irradiated. The ionization per unit time should increase with decreasing wall thickness up to a certain maximum after which it decreases relatively rapidly with decreasing wall thickness. The thickness at which the maximum ionization occurs is that which most nearly satisfies both statement III and IV. This value is called the "optimal or critical wall thickness". See Appendix I for a more thorough discussion of Gray's work.

The evaluation of ${}_{M}S/{}_{G}S$ of equation 1) is difficult because the effective atomic number of bone and its electron density are not known with sufficient accuracy. For this study an indirect method of evaluating this ratio had to be derived.

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12 Ibid.
13 W. V. Mayneord and J. E. Roberts, "An Attempt at Precision Measurements of Gamma Rays," British Journal of Radiology, X (1937), 365-385.

The total stopping power of any medium is given below in terms of its components.

$$ {}_{M}S = {}_{M}S_e \; d_M \; N/A_M \; Z_M \qquad 2) $$

where ${}_{M}S_e$ is the stopping power per electron, d_M is the density of the medium, N is Avogadro's number, A_M is the effective atomic weight of the medium, and Z_M is the effective atomic number.

It is well known that Bakelite is considered an air equivalent material and that it is used in the chamber walls of standard thimble chambers. Therefore in the case of Bakelite

$$ {}_{b}S_e = {}_{a}S_e \qquad 3) $$

and

$$ Z_b/A_b = Z_a/A_a \qquad 4) $$

The subscripts, a,b, and B, refer respectively to air, bakelite and bone. For this reason, the ratio may be stated as follows:

$$ {}_{b}S/{}_{a}S = d_b/d_a \qquad 5) $$

Let us suppose the range (R) of electrons of a specific energy is known in a medium. The range of the electrons in the material must be inversely proportional to the stopping power of the media for electrons. That is,

$$R_M = {}^{K}/_{M}S \, . \qquad 6)$$

From equation 5) and 6) we have

$$R_a = R_b d_b / d_a \, . \qquad 7)$$

Furthermore

$$R_B / R_a = {}_aS / {}_BS \, . \qquad 8)$$

Eliminating ${}_BS/{}_aS$ from 1) and 8) leads to

$$E_{v_B} = R_a / R_B \, W \, J_v \, . \qquad 9)$$

Substituting the value of R_a from 7),

$$E'_{v_B} = R_b d_b / R_B d_a \, W \, J_v \, . \qquad 10)$$

If all values in equation 10) are known except E_{v_B}, this quantity may be evaluated.

III. CAVITY IONIZATION

1. Materials

The equipment used in this investigation consisted of five one-half millicurie Co^{60} needles, a 250 KV x-ray unit, a Victoreen electrometer with a standard Victoreen 100 r Bakelite thimble ion chamber, and an ion chamber made of cortical bone.

It would have been preferable to use human bone in the construction of the bone chamber, but this was not feasible because several layers of bone would have been required to obtain a piece of cortical bone of sufficient size. The use of several cemented surfaces would have introduced the question as to the effect of the bonding material on the results. The cortical portion of the shaft of a bovine femur was thick enough to make the construction of the chamber possible with two slabs of bone. One side of each of two slabs of bone cut from a bovine femur was sanded to a perfect plane with a power sander. The plane sides of the slabs were cemented together with Casein cement. Immediately after the application of the cement, the slabs were placed under pressure which forced out all excess cement. Thus the layer of organic cement was negligibly thick, and its effect on experimental results could also be considered negligible.

For the purpose of this investigation the bone ion chamber was to be a duplicate of the standard 100 r chamber except that the chamber walls were to be of bone instead of Bakelite. The air volume of the standard ion chamber had to be evaluated. With a depth gauge the hole in the chamber was determined to be 27.0 mm deep. This hole is a cylinder with a hemispherical end with a radius equal to the radius of the cylinder. In the open cylindrical end of the chamber a Bakelite plug is inserted so that the enclosed air volume which remains forms the ionization cavity. The depth to which the plug is inserted in the assembled unit was found to be 16.0 mm. The radius of the cylindrical and hemispherical portions of the chamber was 3.91 mm. From these measurements the total cavity volume was calculated by use of the formula

$$V_t = \pi r^2 h + \tfrac{2}{3}\pi r^3 \qquad 11)$$

where r is the radius of the chamber cavity, h is the length of the cylindrical portion of the cavity remaining with the plug inserted, and V_t is the total cavity volume. Hence

$$V_t = \pi (0.391\ cm)^2 (0.71) + \tfrac{2}{3}\pi (0.391\ cm)^3 = 0.466\ cm^3.$$

From the calculated volume, the volume of the portion of the wire electrode extending into the cavity was subtracted to obtain the true air volume. The diameter of the wire was 0.76 mm and its length in the cavity 8.8 mm. Its volume of 0.004 cm^3 subtracted from the above obtained value gives an air volume of 0.462 cm^3.

The slabs of bone cemented together furnished a piece sufficiently thick to permit a cylindrical portion with a diameter of 16.0 mm to be machined on the lathe. One end of the bone was rounded to a hemisphere with a radius equal to that of the outer diameter of the cylindrical portion. From the end opposite the hemisphere, a hole was drilled with a standard 3/16 inch drill whose end had also been rounded to a hemisphere. The radius of the drill was 0.15 mm greater than the radius of the cavity in the standard chamber. The depth of the hole was such that the walls of the chamber were equally thick at every point. The justification for the use of the drill was the increased accuracy with which the air volume of the standard chamber could finally be duplicated.

From another piece of the same femur, the plug to be inserted into the chamber was constructed. Since the bone had a fairly high electrical conductivity, it was necessary to introduce a Lucite sleeve of 3.50 mm diameter in the center of the plug in order to insulate the aluminum wire electrode which was to pass into the cavity through the plug. To accommodate the electrode, a small hole was drilled with a size 60 drill through the center of the Lucite sleeve. The portion of the plug to be inserted into the chamber was made sufficiently longer than the similar portion of the standard chamber plug to compensate for the greater radius of the cavity in the bone chamber. In the assembled unit, the air volume was judged to be accurate within ± 0.5%. See Fig. 1 for a drawing of the chamber and plug in which the linear dimensions are twice actual size.

In the assembled unit the aluminum wire electrode extended into the air cavity of the bone chamber to such an extent that the geometrical center of the hemispherical end of the electrode coincided with the geometrical center of the hemispherical end of the bone chamber. In this manner the distortion of the electric field due to the hemispherical end was reduced as much as possible.

The inside surface of the chamber was coated with an infinitely thin layer of Aquadag in order to insure complete conductivity. The effect of the Aquadag on experimental results was therefore considered negligible.

The bone chamber was threaded and screwed into a condenser unit which was as nearly a duplicate of that of the standard chamber as possible. Briefly, it consisted of a brass barrel inside of which a Lucite sleeve was placed. See Fig. 2 for details. The outside surface of the sleeve formed a continuous conducting medium with the inside surface of the ion chamber; whereas the inside surface of the sleeve formed another continuous conducting medium with the aluminum wire electrode which extended into the cavity. The Lucite between the inside and outside layers of Aquadag served as the dielectric of the condenser. The electrical

FIGURE 1

Cross Section of the Bone Chamber

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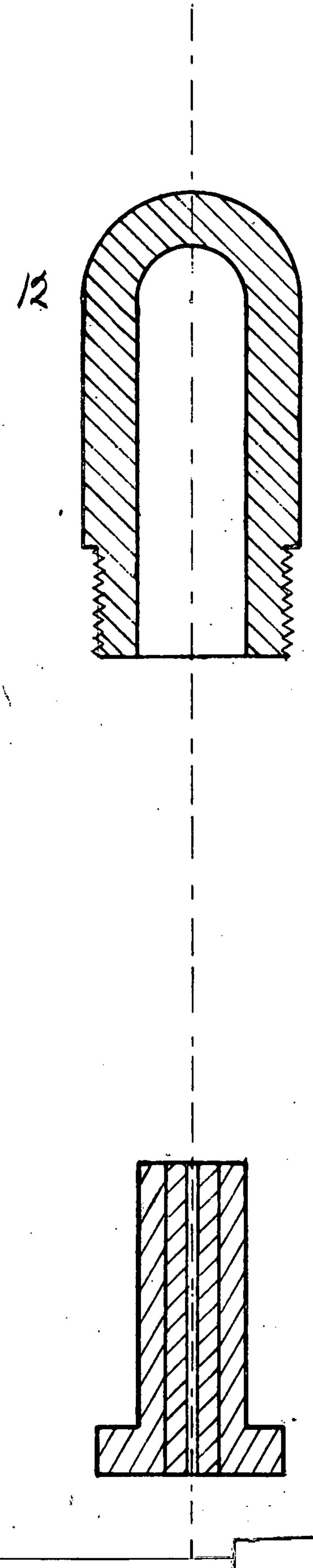

Fig. 1. Cross Section of the Bone Chamber.

Figure 1

FIGURE 2

Cross Section of Ion Chamber-Condenser Unit

A - Ion Chamber

B - Bone Plug

C - Aluminum Wire Electrode

D - Lucite Condenser

E - Brass Cylinder

F - Brass Cap

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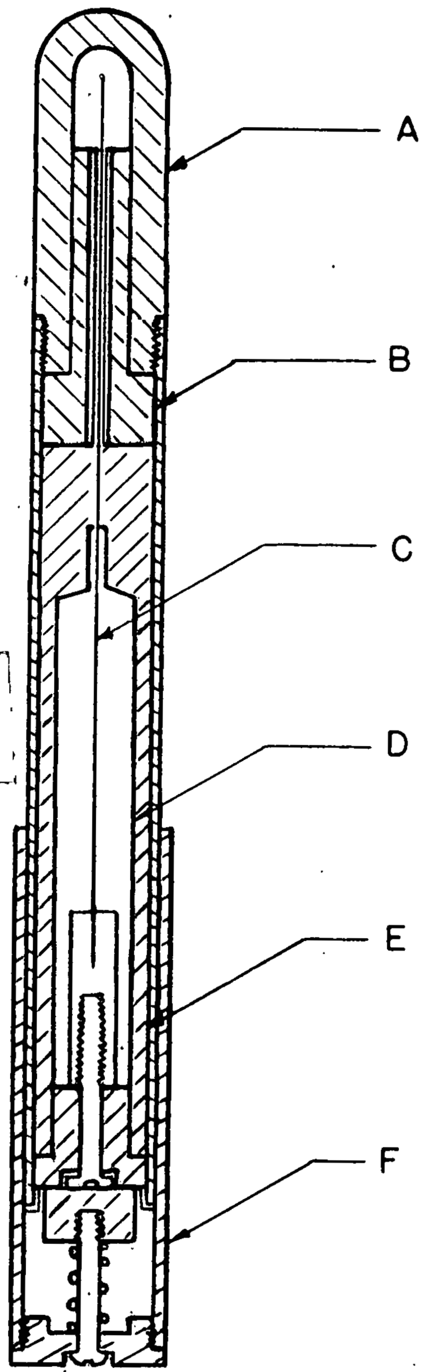

A-Ion Chamber

B-Bone Plug

C-Aluminum Wire Electrode

D-Lucite Condenser

E-Brass Cylinder

F-Brass Cap

Fig. 2. Cross Section of Ion Chamber-Condenser Unit.

capacitance of the bone chamber was checked against the capacitance of the standard chamber, and they were found to be so nearly the same that no difference could be detected. See Appendix II for the procedure used in checking the capacitance.

Since the physical dimensions, the electrical capacitance, and the air cavity volume of the bone chamber were as nearly a duplicate of the standard chamber as was experimentally possible, both chambers could be used interchangeably with the Victoreen electrometer. See Fig. 3 for a photograph of the bone chamber unit.

A Victoreen electrometer has a standard inbuilt device for charging the condenser-ion chamber unit to a potential difference of 400 volts. The electrometer is also used to determine the amount by which the unit is discharged after irradiation. The lowest potential difference at which a reading is taken is 148 volts. This provides an electric field high enough to draw all ions formed to the electrodes of the chamber.

2. Experimental Procedure

The chamber walls were initially four millimeters thick. This thickness was decreased by taking off uniform layers of bone. Twice the thickness was decreased by 0.50 mm. After the second time, only 0.25 mm was taken off at a time. For each wall thickness so obtained, the bone chamber

FIGURE 3

Ion Chamber-Condenser Unit

was irradiated with the beams of gamma and x-rays used in this experiment and the ionization per unit time in the air cavity determined for each of these. A reading was taken with the standard chamber under identical conditions for every bone chamber reading. See Appendix III for the procedure used in reducing the wall thickness of the chamber.

Co^{60} was used as a source of relatively hard radiation. Five one-half millicurie cobalt needles each one-half cm in length were suspended vertically in air by means of a few hundredths mm thick sheet of polystyrene mounted in the plane of a Lucite ring. The ring with its plane horizontal was attached to a stand which had a mechanism for adjusting the vertical height of the ring. The ring was rigidly fixed with respect to any other direction. Two mm from the edge of a 1.8 cm diameter hole in the center of the polystyrene sheet and equally spaced around it, five small holes were punched. In these small holes the needles were supported by their slightly flattened wing tips. The bone or standard chamber was placed in a stand which kept the long axis of the chamber in a vertical position. The assembly containing the Co^{60} needles was lowered over the chamber. Under these circumstances the axes of the suspended needles were parallel to the long axis of the chamber. The distance from any one needle to the center of the ionization chamber was 2.0 cm. Use of the thin sheet of polystyrene reduced the amount of scattering material around the chamber to a minimum. The position of the chamber with respect to the needles was accurately reproducible.

Atmospheric pressure and temperature readings were made each day so that the obtained readings could be corrected.

The following beams of x-rays were used: 140, 200, and 250 KV x-rays each filtered with 0.25 mm Cu plus 1 mm Al and 250 KV x-rays filtered with 6 mm Sn, 0.25 mm Cu and 1 mm Al. The tube current in each case was 15 ma. The chambers were centered in the beam, which was collimated with a standard 2 x 2 cm^2 cone, at a 50 cm skin target distance. For every beam used at least four bone chamber readings were taken. The chamber was rotated a quarter turn clockwise about its long axis after each reading. In this manner any significant variation in the thickness or composition of the bone chamber wall could be detected.

The nearest scattering surface was two meters from the chamber.

Care was taken to repeat the conditions of irradiation as precisely as possible for each series of readings taken, but any variations in the radiation itself were compensated for since the ratio of bone chamber to standard chamber readings was determined each time.

IV RELATIVE ELECTRON RANGES IN BONE AND BAKELITE

1. Theoretical Basis

The basis for the method may be described as follows. If a beam of gamma rays is passed through a material, electrons are ejected in all directions together with degraded gamma rays. In any given direction there will be an upper limit to the energy of the electrons produced in the material which is determined by the gamma ray beam and the angle which the path of the electrons make with the beam.

Let us choose an arbitrary surface (S) in space which is relatively close to a material (M) through which a gamma ray beam (β) is being passed. The electrons (e_{Ω}) which are ejected in a direction which falls within the solid angle (Ω) subtended by the arbitrary surface (S) will cross this surface. The number of electrons being ejected from M and crossing S will depend upon three factors: the composition and intensity of the gamma ray beam, the orientation of the solid angle with respect to the beam, and the effective thickness of the material with respect to the solid angle under consideration. Keeping the first two factors constant and altering the thickness of the material with respect to Ω should affect e_{Ω} in the following manner. As long as the thickness of M is sufficient to keep the primary beam in radiative equilibrium with the electrons produced, e_Ω will remain constant. That is, any electrons formed in the material M at a depth which is greater than the maximum range of the most energetic electrons in that material will not contribute to e_Ω because their energy is completely dissipated before they are able to leave the material.

As the thickness M is decreased to less than this maximum range of the electrons in the material, e_Ω must also decrease because the maximum number of electrons with a finite chance of crossing S is no longer being produced. Therefore, that thickness at which e_Ω begins to decrease is equal to the maximum range of the highest energy electrons ejected in the particular direction under consideration.

Let us assume that the angular distribution of ejected electrons with respect to their maximum energies is essentially the same irrespective of the material through which the beam is passing. This assumption should be very nearly true when the chief absorption process involved is Compton scattering, for electrons are considered as free in this process. It is then possible to determine relative electron ranges in two media.

2. Materials

The five Co^{60} needles were mounted in the bottom of a hole (0.5 in^2) in a lead cylinder. The lead cylinder, which was three inches in diameter and six inches long, was laid horizontally on some lead bricks. Lead bricks were so laid that the cylinder was completely surrounded except for the front end. In this manner a small collimated beam of gamma rays was obtained.

A small brass box was constructed with all sides except the front closed. However, a square hole was cut in the back wall so that when the box was placed against the face of the lead cylinder, the hole in the cylinder coincided with the hole in the box. A hole with a diameter equal to that of the end window of a Geiger tube was placed in the top side of the box. A removable cylindrical brass mounting to secure the Geiger tube over the hole was constructed. Fig. 4 is a photograph of this equipment.

Inside the box a specially constructed aluminum support for the material to be irradiated was mounted on a micrometer head so that very accurately determined vertical adjustments could be made. In its lowest position the platform was one cm below the Geiger tube opening and centered with respect to it. In this position the top of the support was also just below the opening leading to the Co^{60}. The support could be raised 0.75 cm from this position.

The support was constructed from an aluminum block (1.0 inch wide, 1.0 inch long, and 1.25 inches deep) by cutting a rectangular trough 0.5 inches deep and 0.8 inches wide into it. The support therefore consisted of two thin

FIGURE 4

Speciman Support Unit

parallel walls. In the mounted position, the two walls were also parallel to the beam of gamma rays so that it passed between the two walls. The collimated beam of gamma rays was scattered to a small extent by the walls of the support. The magnitude of the scattering was checked by determining the background counting rate with and without the brass box assemblage in place. In both cases the beam was permitted to pass from the lead cylinder. The difference in background was not significant. The thin window (1.9 mg/cm^2) Geiger tube was sensitive to light; consequently, a black piece of paper was used as a cover for the open face of the box. The thin paper also did not change the background noticeably. To eliminate the possibility of any error as a result of scattering, all background determinations were made with the box and paper cover in place and with the beam of gamma rays passing through the brass box.

3. Experimental Procedure

With the use of the equipment described above, the procedure given below was followed. A flat rectangular slab of bone was obtained and placed on its support in the brass box. By adjusting the support height, the bone was centered in the beam of gamma rays. Under these circumstances the Geiger count taken was produced by scattered photons entering the Geiger tube and by the electrons ejected from the bone within the solid angle subtended by the end window of the tube.

The bone was removed and the flat sides were sanded down in a special circular sander which kept the flat sides perfectly parallel to each other. (The photograph in Fig. 5 shows the sander on top of the scalar.) The thickness of the slab was accurately determined before and after it was sanded. The support was raised exactly the same amount by which the thickness of the bone had been decreased. The bone was carefully replaced on its support, and a count was again taken. This procedure was repeated until only an exceedingly thin piece of bone remained. By raising the support by the amounts indicated, the top surface of the bone was kept at a certain specified distance from the tube during all counts that were taken.

A block of Bakelite was subjected to the same experiment. The distance from the Geiger tube to the top surface of the Bakelite while it was in the counting position was kept at the same value used in the previous part.

FIGURE 5

Equipment Used in Determining Relative
Electron Ranges

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V RESULTS

1. Relative Electron Range Determinations

Tables I and II give the experimental results of the procedure just described. The total count from which the counts per minute were determined was usually not below 30,000. A background count was taken after each count taken with the material in place. Finally, when computing the background counting rate, four background counts (taken just before and after the reading under consideration) were totaled and divided by the time. This gave an average total background count of not less than 20,000. On this basis the probable error in the net counting rate was ± 0.62%.

In Fig. 6 counts per minute are plotted versus bone thickness. Within the average probable error associated with the individual counts, a straight approximately horizontal line is obtained from a thickness of 4.1 mm to 1.25 mm.

This agreement with theory is rather surprising because it might be expected that scattered gamma rays would affect the curve. Since less and less scattering material remains in the path of the primary beam as the thickness of the slab is decreased, a gradual but definite decrease in the counts might have been expected. The fact that there is only a negligible decrease indicates either that the amount of scattered gamma rays entering

FIGURE 6

26

Secondary Electron Emission Versus Bone Thickness

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the Geiger tube was relatively negligible or that the greater efficiency of the tube for electrons masked the effect of the scattered photons. Probably a combination of both is involved.

The precise determination of the point at which the curve begins to decline is made difficult because of the statistical variation in the counts. It appears to occur at a thickness of 1.25 mm.

The curve for Bakelite (Fig. 7) indicates 2.00 mm as the point at which the slope of the line begins to change.

There are three factors which must be investigated before the results just given can be interpreted. The first difficulty is encountered in the basis of the method itself. The ranges determined in the above discussion are actually the linear absorber thicknesses which the maximum energy electrons were capable of traversing. Because high speed electrons are scattered repeatedly and quite frequently at large angles, the thickness mentioned is not a measure of actual path length. This linear absorber thickness (${}_tR_M$) is certainly a function of the initial energy of the electrons and of the material itself. Furthermore, as the total number of ejected electrons counted increases, ${}_tR_M$ should become directly proportional to an average of the actual path length (R_M) of the electrons because the amount of scattering which a group of electrons of the same energy undergo is a random or

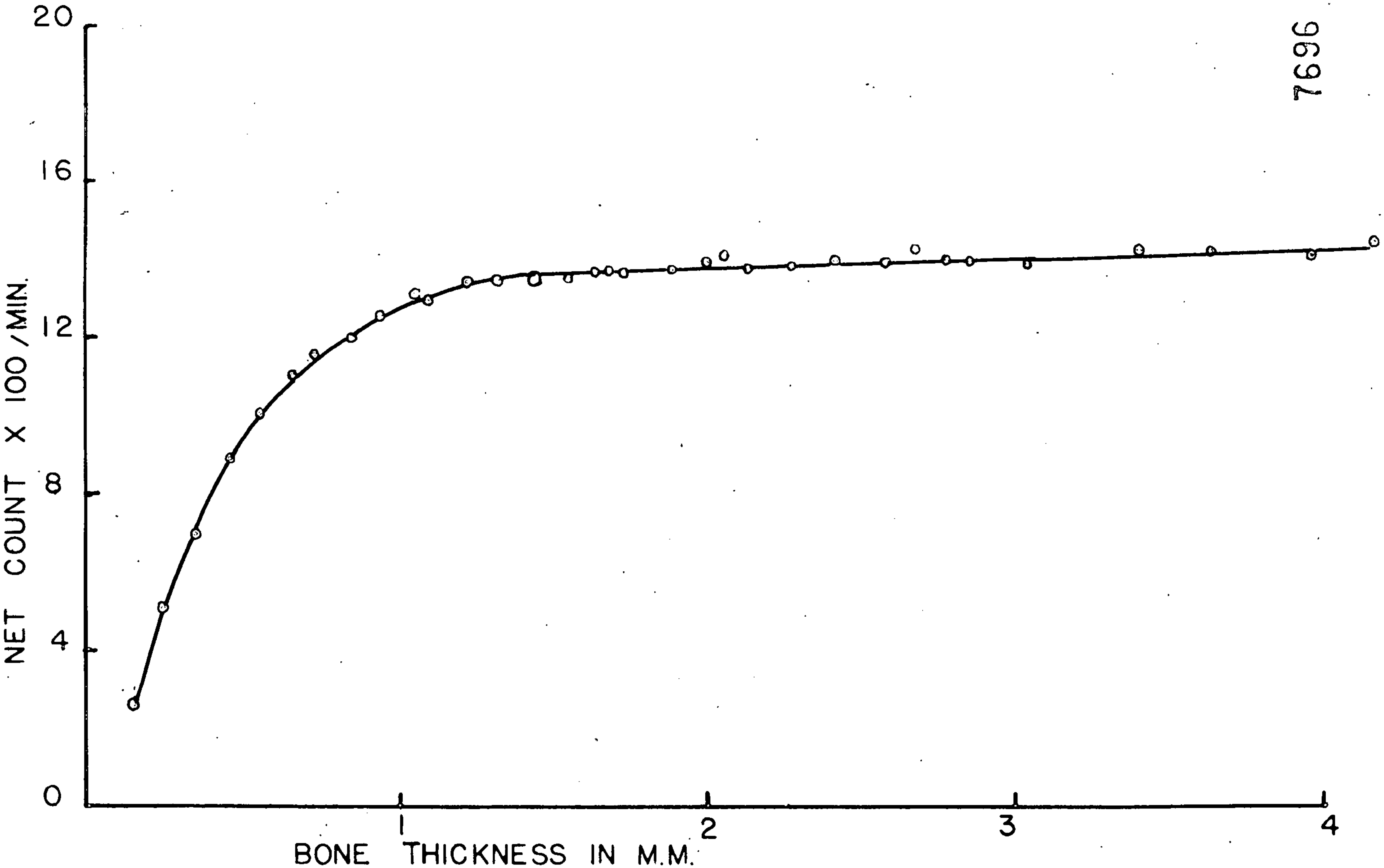
NET COUNT X 100/MIN.
BONE THICKNESS IN M.M.
0
4
8
12
16
20
1
2
3
4

FIGURE 7

28

Secondary Electron Emission Versus
Bakelite Thickness

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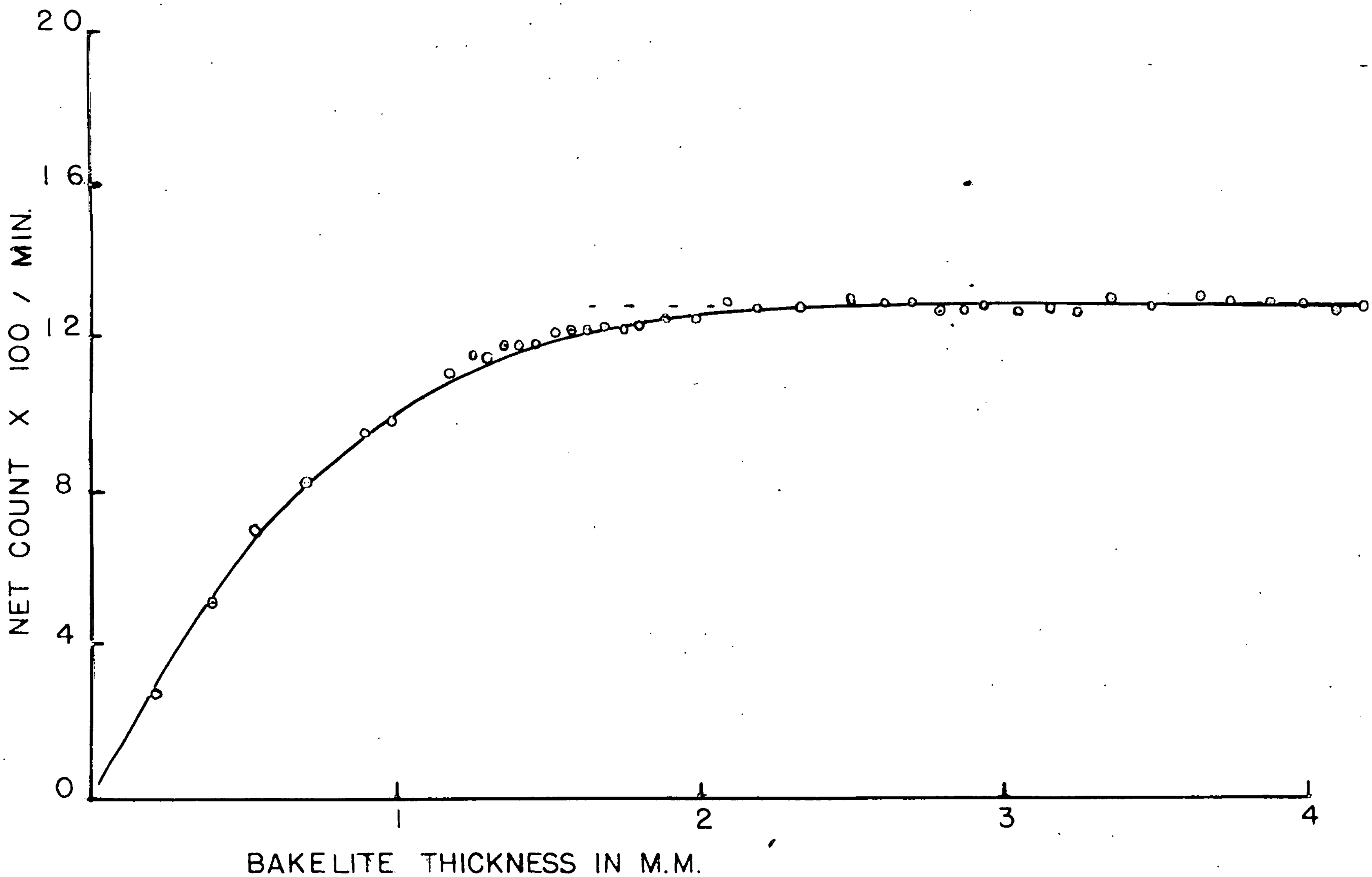

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statistical process. Of course, the angle of deflection of an electron also defines the amount of energy it lost in that particular collision. The resultant straggling in the actual ranges is quite large, but this does not invalidate the quantity termed the average path length of electrons of specified initial energy. However, only if the proportionality constants between $_tR_M$ and R_M were determined for both bone and Bakelite could the relationship,

$$ {}_tR_B / {}_tR_b = R_B / R_b \qquad 12) $$

be stated with known accuracy. Since the effects just described are random in nature, the expression given above should be correct to the first degree of approximation in as much as $_tR_M$ was determined on the basis of large numbers of electrons.

The second complicating factor is the absorption of beta particles by the window of the Geiger tube which results in a measured range which is less than $_tR_M$. Electrons must have sufficient energy left after emerging from the material to penetrate the window; this required energy is retained at the expense of the depth from which they can originate.

The amount of material to be penetrated in the tube window was .0019 gms/cm^2, whereas the amount of material penetrated by maximum energy electrons in bone and Bakelite was respectively .248 gms/cm^2 and .264 gms/cm^2. Thus .0019 is 0.81% and 0.76% of the respective determined ranges. This in itself is far less than the accuracy with which the ranges were determined and may therefore be considered negligible.

The third factor is the geometry of the experimental setup as it affects the observed value of ${}_tR_M$. In the first place, as the path of the ejected electron diverges from a direction normal to the surface of the material being irradiated, the amount of material through which it must pass increases. Secondly, the solid angle which the surface, projected by the sensitive volume of the tube at the end window, subtends with the place of origin of an ejected electron is a function of the distance between the end window and the origin. This function is independent of the material irradiated, but the probability of electrons entering the sensitive tube volume from the maximum depth in a material decreases as the maximum depth increases.

This geometrical effect is not easily calculated mathematically, but a relatively simple experimental procedure was carried out in order to gain information concerning the effects. A thin piece of Bakelite (0.380 mm) was placed on the support in the brass box of the experimental equipment, and a count was taken. The support was adjusted to various heights. At each of these settings a count was taken. There were three settings which were of particular significance. One count was determined with the micrometer set at a value it had when the slope of the curve in Fig. 6 began to change. Another was taken at the setting which the micrometer had when the curve in Fig. 7 began to drop. Finally, one was taken with the top surface of the material at the same distance from the tube that it had in the previous experiments. The increase in the counting rate as the distance between the irradiated material and the Geiger tube decreases is a measure of the increased probabilities of electrons entering the Geiger tube because the solid angle subtended is changing. From the results of this experiment (see Fig. 8), the probability of an electron entering the sensitive volume of the Geiger tube from the maximum depths in the material was 80% of the probability of an electron entering from the top surface. The value of the relative probabilities as given above is slightly smaller than that for bone and slightly larger than that for Bakelite. It can be seen that the geometrical effect decreases the relative number of electrons coming from a maximum depth in a material. Consequently, the initial changes in the slopes of the curves in Figs. 6 and 7 are retarded by the geometry involved in the experiment. This decreases the accuracy with which the initial changes in the slopes of the curves can be detected, but it does not shift the thickness at which the slopes actually begin to change. The implication is that the errors due to the

FIGURE 8

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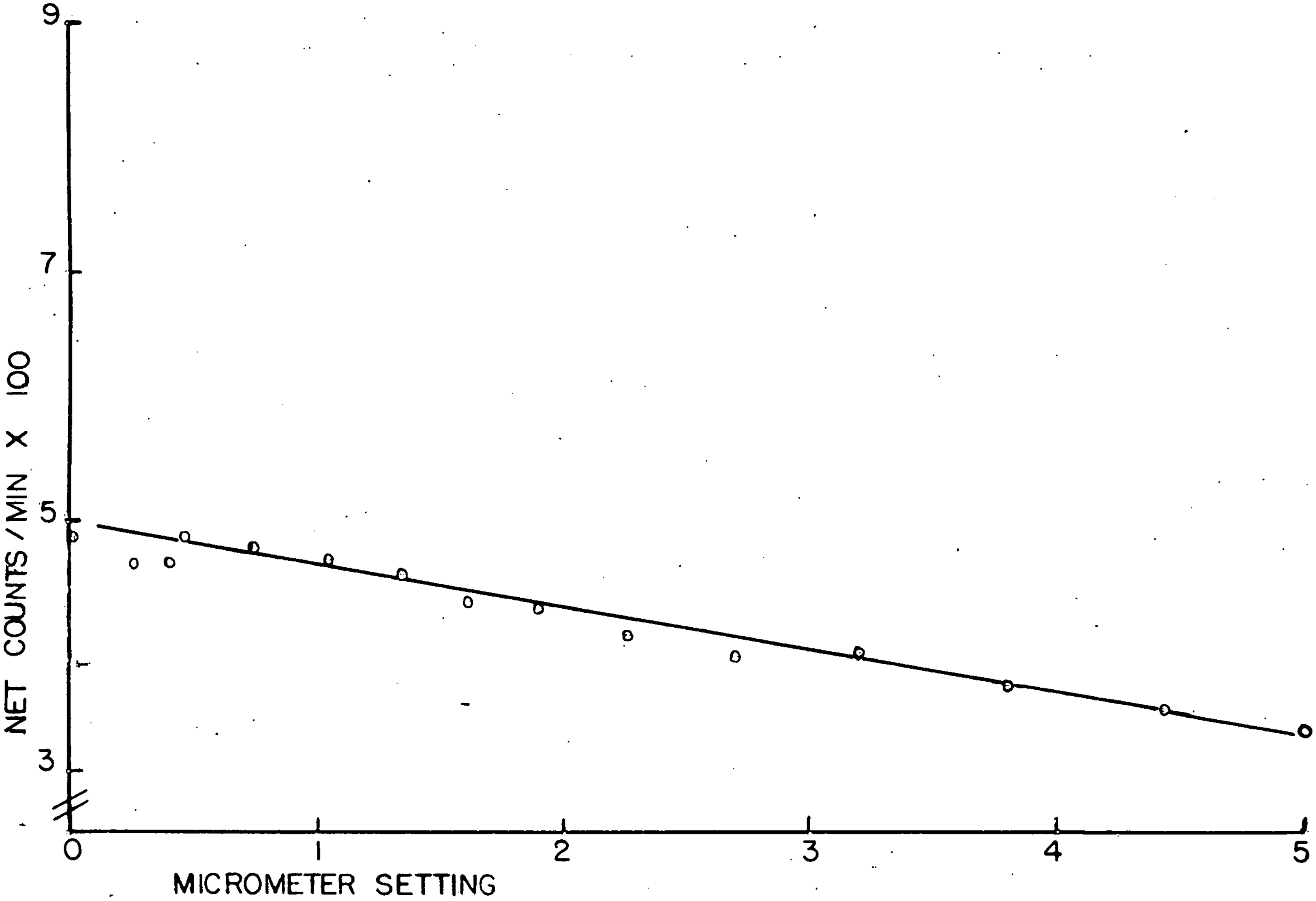
Study of the Effect of Geometrical Errors



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geometrical effect are taken into account when the errors in reading the curves are cited. It would be expected that ${}_tR_b$ would be more difficult to determine from Fig. 7 than ${}_tR_B$ from Fig. 6. A look at the two curves verifies this statement.

As a consequence of the above discussion, there is reason to believe that the ratio ${}_tR_b / {}_tR_B$ is very nearly equal to R_b / R_B. Though the actual range has not been determined, the relative ranges should be accurate as a first approximation. The unfortunate fact is that the error involved cannot be evaluated satisfactorily. The estimated uncertainties in determining ${}_tR_B$ and ${}_tR_b$ from the curves are respectively ± 0.10 mm and ± 0.13 mm.

It is of interest to determine, if possible, the effective atomic number of bone as established by the above ratio and compare it to that determined by Spiers[14]. Assuming that $Z_b/A_b = Z_B/A_B$, from equation 2) it may be shown that

$$ {}_BS_e / {}_bS_e = R_b d_b / R_B d_B \qquad 13) $$

The densities of bone and bakelite were determined as follows. A piece of bone from which the chamber had been constructed was turned down to a cylinder on the lathe. The ends were

14 F. W. Spiers, "Effective Atomic Number and Energy Absorption in Tissues," British Journal of Radiology, X (1937), 365-385.

squared very carefully. The dimensions of this solid cylindrical piece of bone were carefully measured. This piece was then weighed on an analytical balance. From these measurements the volume was calculated to be 2.740 cc and the weight to be 5.417 gm. Therefore the density was 1.98 gms/cc. In a similar manner, the density of bakelite was determined from a piece with a volume of 1.809 cc and a weight of 2.396 gms to be 1.32 gms/cc. Using the values for ${}_{t}R_{b}$ and ${}_{t}R_{B}$ obtained above, ${}_{B}S_{e}/{}_{b}S_{e}$ is calculated to be 1.065. With the use of Gray's[15] graph of the variation of S_e with the atomic number relative to ${}_{a}S_{e}$, the effective atomic number is 10 as compared to the value of 13.9 established by Spiers[16]. This difference might in part be explained by the fact that Spiers used Walter's expression for the effective atomic number. This gives a value too high if Compton scattering is the main process. The value obtained in this experiment is in close agreement with that used by Johns, Darby and Kornelsen[17].

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15 L. H. Gray, "An Ionization Method for the Absolute Measurement of Gamma Ray Energy," Proceedings of the Royal Society of London, Series A, CLVI (1936), 589.

16 F. W. Spiers, "Effective Atomic Number and Energy Absorption in Tissues," British Journal of Radiology, XIX (1946), 52-62.

17 Johns, Darby, and Kornelsen, "Physical Aspects of Treatment of Cancer by 22 Mev X-rays," British Journal of Radiology, XXIV (1951), 355-364.

2. Cavity Ionization: Gamma Radiation

Tables III, IV, V, VI, and VII are records of the cavity ionization in bone for various chamber wall thicknesses and for the various beams of gamma and x-rays used in this experiment.

Table IV shows that the ionization in the bone chamber cavity is very little greater than that in an air equivalent chamber when it is irradiated with gamma rays of the energy emitted by Co^{60}.

In Fig. 9 the bone cavity ionization is plotted versus chamber wall thickness. Attention should be drawn to the fact that small changes in ionization have been magnified by the choice of the ordinate unit size. This was done so that the optimal wall thickness might be more easily established which in turn facilitated a more accurate extrapolation to zero wall thickness. The latter is necessary in order to obtain a value which would be representative of the ionization in the cavity if there were no attenuation of the beam. This extrapolation is justified inasmuch as the Co^{60} gamma rays are nearly monochromatic.

The portion of the curve for wall thicknesses greater than 2.25 mm represents the slow absorption of the hard gamma rays and the portion preceding this shows the decrease in ionization after radiative equilibrium between the primary beam and the secondary electrons is no longer possible.

FIGURE 9

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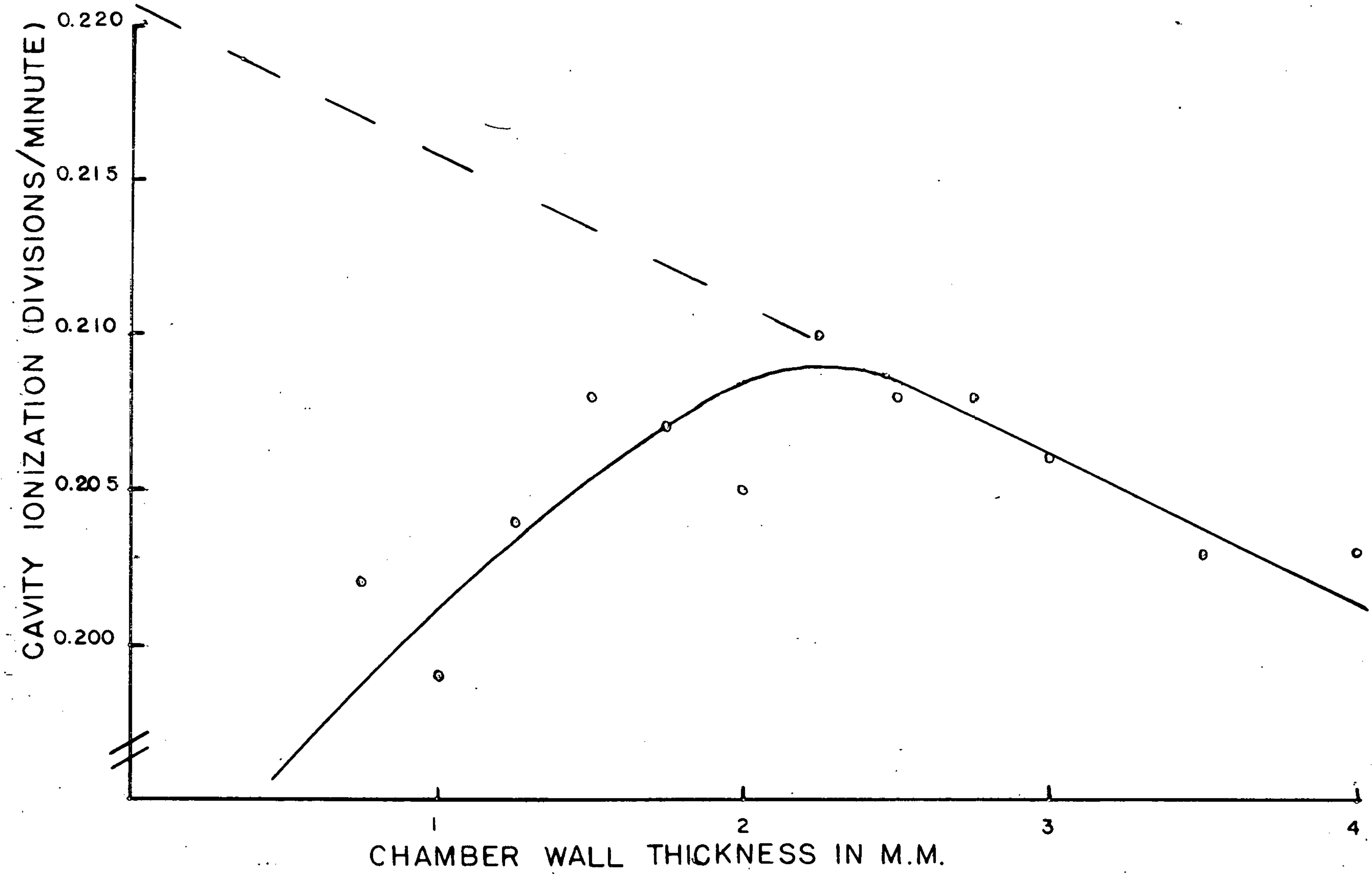
Cavity Ionization in the Bone Chamber Versus
Chamber Wall Thickness
(Radiation: Co^{60} Gamma Rays)


0.220
0.215
0.210
0.205
0.200
CAVITY IONIZATION (DIVISIONS/MINUTE)
1
2
3
4
CHAMBER WALL THICKNESS IN M.M.

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The slow decrease in the ionization rate with decreasing wall thickness for values below the optimal may be explained by considering the experimental conditions under which the cavity ionization was determined. Ordinarily, measurements of cavity ionization are made in a collimated beam, and under these circumstances the number of electrons generated in the air surrounding the chamber is negligible compared to those produced in the chamber wall. In the case of the Co^{60} needles in open air, there is an atmosphere of high speed electrons produced in the air surrounding the chamber. Obviously, these electrons cannot contribute to the ionization in the cavity until the thickness of the chamber walls is less than the maximum range of maximum energy electrons in the bone. However, as the wall thickness becomes less than this value, electrons produced in the air begin to contribute to the cavity ionization. The thinner the walls become the greater is the percentage of the total ionization which is produced by electrons entering the cavity from the air surrounding the chamber. At the same time, compensation is never complete.

The bone plug which forms one part of the chamber wall affects the shape of the curve in a manner similar to the effects attributed to electrons generated in air. The rate at which the ionization in the cavity decreases with decreasing values of wall thickness below the optimal one is retarded by the fact that the primary beam is always in radiative equilibrium with the secondary electrons produced in the portion of the wall formed by the bone plug. Unlike the preceding case, the effect of the bone plug will also tend to decrease the rate at which the ionization occurs with decreasing wall thickness for values greater than the optimal. This latter effect must be quite small because the bone plug forms only a small fraction of the chamber surface, and any difference in the number of electrons per cm^2 of surface area it contributes to the cavity and that contributed by the other portions of the wall must be attributed to the difference in the attenuation of the primary beam. For the hard gamma rays this is very small.

From the above discussion it follows that the apparently atypical portion of the curve does not affect the validity with which the other portion may be extrapolated to zero wall thickness.

The extrapolated value is 0.220 units deflection per minute and is 1.18 times the ionization rate of 0.187 observed in the standard chamber with a Lucite sleeve added to establish optimal wall thickness.

Because it was not feasible to make more than an average of three or four readings at any one wall thickness, mathematical calculation of a probable error would have little significance. On the average, the greatest amount by which any reading within a group varied from the average was 1.8%. The electrometer scale could be read with an accuracy varying between 99.0 and 99.5% depending on the portion of the scale being used. The fact that many points are used to determine the extrapolated curve (Fig. 9) decreases the error below that quoted above.

There is the possibility of an indeterminate error in the ionization value of 0.220 which has to do with the failure of the bone chamber to satisfy ideal conditions under which Gray's derivations are valid. Ideally, the gas in the cavity should have the same effective atomic number as the walls of the chamber. How closely any given chamber approaches the ideal may be studied by observing the variation in ionization as the pressure of the gas in the cavity is changed. Gray[18] found no variation in a graphite chamber cavity as the pressure was reduced from atmospheric to 10 cm Hg. With lead chambers the ionization to pressure ratio increased by seven per cent. If the effective atomic number of bone is between 10 and 13.9 as compared to 7.3 for air, the ionization to pressure ratio should certainly not increase more than one per cent if this test were applied to the bone chamber. The error residing in this factor should then be less than one per cent.

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18 L. H. Gray, "An Ionization Method for the Absolute Measurement of Gamma Ray Energy," Proceedings of the Royal Society of London, Series A, CLVI (1936), 581.

Since the ionization chambers had to be exposed from four to eight hours in order to obtain good readings, investigations of the leakage were made. In part, the leakage depends upon the voltage across the chamber; therefore the leakage in the chambers was determined at various potentials. From the results of these tests it became apparent that the leakage factor was far smaller than the experimental error in reading the electrometer. For example, in an eight hour reading the average leakage rate per hour was 0.016 divisions whereas the radiation discharge rate was 12.4 div/hr.

Using equation 10 and the values obtained from the curves in Figs. 6, 7 and 9, the energy absorption in bone per unit mass when it is irradiated with Co^{60} gamma rays may be evaluated. In the Victoreen electrometer one unit deflection represents 2.083×10^9 ion pairs per cc in the ionization cavity of any instrument which has the same air volume as that of the standard 100 r chamber. Since the bone chamber meets this requirement, the energy absorption in ergs per cc per division deflection may be written

$$E_v = \frac{(2.00\ \text{mm})(1.32\ \text{gm/cc})}{(1.25\ \text{mm})(0.00129\ \text{gm/cc})}(5.20 \times 10^{-11}\ \text{ergs/ion pair})(2.083 \times 10^{9}\ \text{ion pairs/cc/div.})$$

$$E_v = 177\ \text{ergs/cc/div.}$$

Because the ionization rate in the bone chamber is 1.18 times as great as in the standard chamber, the energy absorption per cc of bone per roentgen is

$$E_{v/r} = (1.18\ \text{div}/r)(177\ \text{ergs/cc/div}) = 209\ \text{ergs/cc/r}$$

Finally, the energy absorption per gm per roentgen is

$$E_{m/r} = (209\ \text{ergs/cc/r})/(1.98\ \text{gm/cc}) = 105\ \text{ergs/gm/r}$$

Provided the indeterminate error in ${}_tR_b / {}_tR_B$ is negligible, the above values are estimated to be accurate within $\pm$ 5%.

Spiers'[19] value is given as approximately 150 ergs/cc/r. This is rather surprising inasmuch as the indeterminate errors in the value of 209 ergs/cc/r would most probably tend to increase the observed value rather than to decrease it.

It is also instructive to calculate the energy absorption in bone assuming Spiers[20] determination of the effective atomic number and electron density of bone to be correct and the cavity ionization presented here to be accurate. From Gray's[21] graph the correction factor for a chamber of

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19 F. W. Spiers, "Effective Atomic Number and Energy Absorption in Tissues," British Journal of Radiology, XIX (1946), 52-62.
20 Ibid.
21 L. H. Gray, "An Ionization Method for the Absolute Measurement of Gamma Ray Energy," Proceedings of the Royal Society of London, Series A, CLVI (1936), 589.

such wall material is 1.095. Thus the energy absorption per cc per r would be

$$E_v = \left[\frac{3\times10^{23}\ \text{electrons/cc}}{3.92\times10^{20}\ \text{electrons/cc}}\right](1.096)(5.20\times10^{-11}\ \text{ergs/ion pair})\frac{(2.083\times10^{9}\ \text{ion pairs/cc/div})}{(1.18\ \text{div/r})}$$

$$E_v = 107\ \text{ergs/cc/r}.$$

3. Cavity Ionization: X-radiation

There may be slight variations in the quality and quantity of the x-rays produced by an x-ray unit over an extended period of time; hence it was felt that greater accuracy could be obtained if the ratio of the bone cavity ionization to that in the standard chamber was plotted versus chamber wall thickness. In Fig. 10 the results recorded in Tables IV - VII are plotted in such a manner.

So many of the soft components of the 250 KV x-rays were filtered out with a Thoreaus III filter that the beam was very nearly monochromatic. The constant slope of the curve verifies this fact. Extrapolation to zero wall thickness gives a ratio of 1.75. The linear dimensions of the bone chamber were probably small enough in this case to justify the extrapolation. If the cavity were too large the walls would not make the proper contribution to the ionization, and the observed value would be too small. Multiplying the observed ratio by the energy absorption per unit volume per division then gives 310 ergs/cc/r or 157 ergs/gm/r as the lower limit to the energy absorption in bone under the conditions specified.

FIGURE 10

Relative Cavity Ionization in the Bone Chamber
Versus Chamber Wall Thickness
(Radiation: X-rays)

A - 140 KV X-rays, 0.25 mm Cu + 1 mm Al

B - 200 KV X-rays, 0.25 mm Cu + 1 mm Al

C - 250 KV X-rays, 0.25 mm Cu + 1 mm Al

D - 250 KV X-rays, Thoreaus III Filter

The other curves have also been extrapolated, but the values so obtained must definitely be considered as indicative only. Three reasons account for this reservation. The chamber cavity may have been too large for the relatively soft beams of x-rays used, the beams were not homogeneous, and the changing slope of the curve in itself makes the extrapolation somewhat inaccurate. Again the absence of these factors would make the observed values higher; therefore they may be considered as indicative of the lower limit to the energy absorbed under the conditions outlined.

The magnitude of the possible errors in taking the readings was the same as those given in the description of of the gamma irradiation results: namely, 1.8%.

If the energy absorption is calculated in the manner previously indicated, the values of 273, 300, and 328 ergs/gm/r are obtained respectively for 250, 200, and 140 KV X-rays each filtered with 0.25 mm Cu plus 1 mm Al. As shown above, these values represent somewhat inaccurate determinations of the lower limits of energy absorption in bone under the conditions specified.

VI SUMMARY AND CONCLUSIONS

The energy absorption in bone was determined using a thick-walled thimble ionization chamber, constructed of cortical bovine bone, by measurement of ionization in the air cavity of the chamber as the wall thickness was reduced. When Co^{60} gamma rays were used the energy absorption was found to be 105 ± 5 ergs/gm/r. The lower limits to the energy absorption in bone irradiated with x-rays were determined to be 157 ergs/gm/r for 250 KV x-rays filtered with a Thoreaus III filter, 273 ergs/gm/r for 250 KV x-rays filtered with 0.25 mm Cu + 1 mm Al, 300 ergs/gm/r for 200 KV x-rays filtered with 0.25 mm Cu + 1 mm Al, and 328 ergs/gm/r for 140 KV x-rays filtered with 0.25 mm Cu + 1 mm Al. The value quoted above for 1.2 Mev radiation indicates that Spiers[22] value may be too low.

The linear absorber thickness of bone through which maximum energy electrons produced by Co^{60} gamma rays are capable of passing was established at 1.25 mm or 0.248 gm/cm^2. The effective atomic number of bone was determined to be 10.

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22 F. W. Spiers, "Effective Atomic Number and Energy Absorption in Tissues," British Journal of Radiology, XIX (1946), 52-62.

TABLE I

Secondary Electron Emission Versus Bone Thickness

Bone Thickness	Total (Counts/Min.)	Background (Counts/Min.)	Net (Counts/Min.)
4.170 mm	2039	590	1449
3.968	2009	591	1418
3.642	2012	591	1421
3.388	2016	592	1424
3.037	1985	597	1388
2.859	1995	600	1395
2.784	2002	602	1400
2.672	2021	606	1415
2.569	2002	608	1394
2.422	2009	611	1398
2.280	1995	614	1381
2.143	1986	609	1377
2.061	2022	612	1410
2.006	2006	612	1394
1.884	1991	614	1377
1.732	1985	619	1366
1.684	1991	615	1376
1.624	1987	616	1371
1.557	1975	620	1355
1.452	1980	624	1356
1.326	1976	631	1345
1.231	1981	637	1344
1.114	1936	638	1298
1.066	1956	639	1317
0.994	1898	639	1259
0.861	1845	638	1207
0.737	1801	640	1161
0.661	1751	643	1108
0.558	1649	646	1003
0.460	1535	652	883
0.350	1358	657	701
0.240	1168	660	508
0.140	925	665	260

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TABLE II

Secondary Electron Emission Versus Bakelite Thickness

Bakelite Thickness	Total (Counts/Min.)	Background (Counts/Min.)	Net (Counts/Min.)
4.733 mm	1877	582	1295
4.623	1861	582	1279
4.507	1884	587	1297
4.399	1888	590	1298
4.296	1869	590	1279
4.193	1874	595	1279
4.094	1864	593	1271
3.990	1876	592	1284
3.870	1877	587	1290
3.751	1873	585	1288
3.654	1884	586	1298
3.492	1865	585	1280
3.354	1889	591	1298
3.241	1852	592	1260
3.160	1866	593	1273
3.047	1858	597	1261
2.942	1880	600	1280
2.870	1865	600	1265
2.788	1868	601	1267
2.704	1893	599	1294
2.609	1882	596	1286
2.501	1894	596	1298
2.333	1874	596	1278
2.195	1876	599	1277
2.093	1898	604	1294
1.984	1852	608	1244
1.892	1859	611	1248
1.810	1848	615	1233
1.755	1838	615	1223
1.688	1847	613	1234
1.624	1837	612	1225
1.575	1831	611	1220
1.519	1816	610	1206
1.461	1795	616	1179
1.412	1800	622	1178
1.362	1804	624	1180

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TABLE II (Continued)

Bakelite Thickness	Total (Counts/Min.)	Background (Counts/Min.)	Net (Counts/Min.)
1.303	1771	625	1146
1.253	1777	625	1152
1.177	1726	623	1103
0.983	1611	629	982
0.883	1598	639	959
0.706	1463	643	820
0.541	1340	644	696
0.400	1162	651	511
0.206	923	655	268

TABLE III

Cavity Ionization in the Bone Chamber Versus Chamber Wall Thickness Radiation: Co^{60} Gamma Rays

Bone Chamber Wall Thickness	Bone Chamber Divisions/Min. (Average)
4.00 mm	0.203
3.50	0.203
3.00	0.206
2.75	0.208
2.50	0.208
2.25	0.210
2.00	0.205
1.75	0.207
1.50	0.208
1.25	0.204
1.00	0.199
0.75	0.202

An average of 12 readings taken with the 100 r standard chamber at various times gives a value of 0.187 r/min. under irradiation conditions identical to that which the bone chamber was subjected.

All chamber readings were corrected to standard temperature and pressure.

An average of at least three or four readings was taken in each case.

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TABLE IV

Relative Cavity Ionization in the Bone Chamber
Versus Chamber Wall Thickness
(Radiation: 250 KV X-rays, Thoreaus III Filter)

Bone Chamber Wall Thickness	Bone Chamber Div./Min.	Standard Div./Min.	Ratio
4.00 mm	49.7	29.75	1.67
3.50	50.0	29.75	1.68
3.00	50.0	30.0	1.67
2.75	50.0	30.0	1.67
2.50	49.1	29.0	1.70
2.25	49.6	29.2	1.70
2.00	48.9	29.0	1.68
1.75	48.1	28.5	1.69
1.50	48.0	27.8	1.72
1.25	47.6	28.0	1.70
1.00	49.8	28.75	1.74
0.75	48.25	28.9	1.67

TABLE V

Relative Cavity Ionization in the Bone Chamber
Versus Chamber Wall Thickness
Radiation: 250 KV X-rays, 0.25 mm Cu 1 mm Al Filter

Bone Chamber Wall Thickness	Bone Chamber Div./Min.	Standard Div./Min.	Ratio
4.00 mm	209.0	83.75	2.50
3.50	216.0	83.5	2.59
3.00	220.5	83.0	2.65
2.75	220.8	83.4	2.65
2.50	220.8	81.8	2.70
2.25	223.5	82.0	2.72
2.00	222.75	80.5	2.77
1.75	224.7	81.0	2.78
1.50	224.25	79.8	2.81
1.25	228.75	80.0	2.86
1.00	234.4	81.5	2.88
0.75	231.75	79.6	2.91

TABLE VI

Relative Cavity Ionization in the Bone Chamber
Versus Chamber Wall Thickness
(Radiation: 200 KV X-rays, 0.25 mm Cu 1 mm Al)

Bone Chamber Wall Thickness	Bone Chamber Div./Min.	Standard Div./Min.	Ratio
4.00	140.0	52.0	2.70
3.50	144.0	51.8	2.78
3.00	145.0	52.25	2.78
2.75	147.5	52.5	2.81
2.50	147.2	51.1	2.88
2.25	149.0	51.5	2.90
2.00	148.5	50.0	2.97
1.75	152.5	49.8	3.06
1.50	151.5	49.1	3.05
1.25	153.2	49.25	3.12
1.00	155.5	50.0	3.11
0.75	156.8	49.75	3.15

TABLE VII

Relative Cavity Ionization in the Bone Chamber
Versus Chamber Wall Thickness
(Radiation: 140 KV X-rays, 0.25 mm Cu 1 mm Al)

Bone Chamber Wall Thickness	Bone Chamber Div./Min.	Standard Div./Min.	Ratio
4.00 mm	76.1	25.8	2.95
3.50	78.0	26.0	3.00
3.00	80.0	26.5	3.02
2.75	78.8	25.7	3.07
2.50	80.4	26.0	3.09
2.25	82.1	26.0	3.16
2.00	82.0	25.5	3.22
1.75	82.4	25.3	3.26
1.50	83.25	25.2	3.30
1.25	85.6	25.45	3.36
1.00	86.0	25.1	3.42
0.75	85.6	24.9	3.44

APPENDIX I

Summary of Gray's Investigation of Cavity Ionization

In order to derive the relationship expressed in Equation 1, Gray[23] made one experimentally justifiable assumption. It is assumed that a β-particle traversing a solid medium loses in the distance ΔX (short with respect to its range) the same amount of energy as it would in passing through $\rho \Delta X$ of air, where ρ is the proportionality factor which is independent of the speed or velocity of the β-particles. Under these circumstances the energy equivalent of the ionization per unit volume in the cavity is $1/\rho$ times the gamma ray energy absorbed per unit volume of the solid. The rigorous mathematical proof of this is rather long and involved since it must be established that the distribution of both the velocity and the direction of the β-particles is not disturbed in crossing the surface of the cavity wall.[24] Accepting this as a true statement intuitively and realizing that it was mathematically shown to be correct, the derivation of the above stated relationship can be obtained as indicated below.

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23 L. H. Gray, "An Ionization Method for the Absolute Measurement of Gamma Ray Energy," Proceedings of the Royal Society of London, Series A, CLVI (1936), 578-598.

24 L. H. Gray, "The Absorption of Penetrating Radiation," Proceedings of the Royal Society of London, Series A, CXXII (1928), 647-668.

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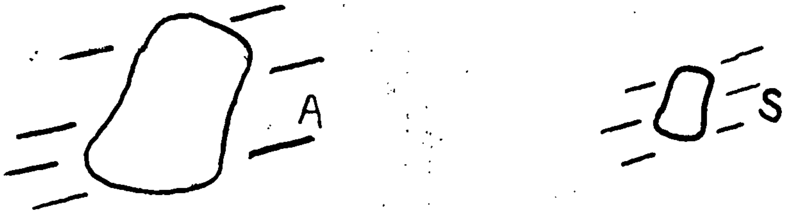
Consider two geometrically similar volumes in a solid medium with linear dimensions in the ratio of $\rho : 1$ where the first is an air cavity introduced in the medium and the second is a volume element of the medium. The gamma ray flux is uniform over the whole medium and the volume elements, A (air cavity) and S (solid volume element) are small compared to the range of particles in the medium.



Since the distribution of the velocity and direction of the β-particles is not disturbed in crossing the surface of the cavity wall, it follows that the same amount of energy is lost by particles originating in equivalent positions in the medium and crossing the respective volume elements. However, there must be ρ^2 times as many particles crossing A as S from geometrical considerations. At the same time the volumes are in the ratio of $\rho^3 : 1$. Hence the ratio of energy losses in the two mediums must be $1/\rho$. The contribution from ionization of the air by the primary beam is negligible because of the small linear dimensions and the small coefficient of linear absorption. Furthermore, if the Compton effect is predominant, the small contribution added will also be approximately in the ratio of $1/\rho$. The relationship may then be expressed as follows:

$$J_v W = 1/\rho \, E_v$$

where J_v is the ionization per unit volume in the air of the cavity, W is the average energy lost by an electron per pair of ions formed, E_v is the energy absorbed per unit volume in the solid medium, and ρ is the proportionality constant which is independent of the speed of the β-particles.

The equation indicates that ρ should vary inversely with the pressure of the gas. Gray investigated this experimentally. For low atomic number materials the ratio of ionization to pressure is a constant, but for lead there was about seven per cent variation in changing the pressure from 74 cm Hg to 10.

J_v should also be independent of the size of the cavity. Using chambers with volumes varying from 0.96 cc to 0.005 cc, the ionization seemed to be constant within the limits of the experimental error involved.

The quantity ρ is the ratio of energy lost by an electron in traversing a given distance in two different media, in this case the solid and the cavity gas. Since the stopping power of a medium is defined as $-\Delta E/\Delta X$ where ΔE is the energy lost in traveling the distance ΔX in the stopping medium, it follows that ρ is equal to the ratio ${}_mS/{}_aS$. Information about relative stopping powers should then give information about ρ also. Using Bethe's electronic stopping power formula which has been experimentally verified for certain elements, electronic stopping powers relative to air were calculated for various energies of electrons and for various atomic number materials. The results show that the ratio of electronic stopping powers of various media to that of air does not vary more than 4% over a wide range of energies for $Z = 1$ to $Z = 18$. Above this greater variations are noticed. To this extent the original assumption about ρ is correct.

The electronic stopping power experimentally seems to vary but slowly with atomic number, decreasing with increasing atomic number. The variation of ρ with atomic number was also investigated. J_V in an air cavity enclosed by a material of atomic number Z has been shown to be given by

$$\Delta E_z / W_\rho = \Delta E_z / W \cdot {}_aS / {}_mS$$

where ΔE_Z is the energy of the radiation absorbed per unit volume in the solid material surrounding the cavity. The ionization in chambers of different wall materials is then proportional to

$$\Delta E_z / {}_zS = \Delta E_z / {}_zS_e n_z$$

where ${}_zS_e$ is the stopping power per electron and n_Z is the number of electrons per unit volume. However, it is known that

$$\Delta E_Z = E(\sigma_a + \tau) = E\, n_Z\, ({}_e\sigma_a + {}_e\tau).$$

(E is the flux of γ-ray energy); consequently, if ${}_e\tau$ is negligible and since ${}_e\sigma_a$ is independent of Z, the ionization is proportional to

$$E n_Z\, {}_e\sigma_a / {}_Z S_e n_Z = K / {}_Z S_e$$

The ionization in different chambers should be inversely proportional to the electronic stopping power.

Chambers of various materials were made and the ionization checked. The results were compared to the reciprocal of the electronic stopping powers calculated previously. The agreement was found to be excellent.

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APPENDIX II

Electrical Capacitance of the Bone Chamber

The capacitance of the bone chamber was checked as follows: The bone chamber was inserted into the electrometer and charged to 400 volts (V_0) (zero on electrometer scale). The total charge (Q_t) stored in the electrometer and the bone chamber may be given by

$$Q_t = (C_e + C_b)\,V_0$$

where C_e is the capacitance of the electrometer and C_b is the capacitance of the bone chamber.

After the bone chamber was withdrawn, the electrometer was discharged. The charge (Q_f) remaining was then equal to $C_b V_0$.

The charged bone chamber was reinserted into the electrometer. The voltage (V_{f_1}) as read on the electrometer scale may be given as follows:

$$V_{f_1} = Q_f/(C_e + C_b) = C_b V_0/(C_e + C_b)$$

The same procedure was followed with the standard 100 r chamber. The final voltage (V_{f_2}) in this case may be given by

$$V_{f_2} = C_s V_0/(C_e + C_s)$$

where C_S is the capacitance of the standard chamber. Therefore if $C_S = C_b$ then V_{f_2} must equal V_{f_1}. This result was obtained in the check. No difference in C_b and C_S could be detected in the electrometer readings.

APPENDIX III

Procedure for Changing the Bone Chamber Wall Thickness

The brass barrel in which the bone chamber was mounted was chucked in the lathe exactly in the same marked position each time the walls were turned down.

After the chamber was chucked, a designated layer of bone was very carefully cut off the cylindrical portion of the chamber. A slice of equal thickness was cut off from the hemispherical tip of the chamber. This end was sanded to a hemisphere again and checked with a radius gauge set to the radius of the cylindrical portion. Only the extreme tip, which had already been cut down to the required thickness, was not sanded. Hence when the radius gauge was in complete contact with the end, the proper amount had been taken off.

The accuracy of this method in maintaining a uniform wall thickness was checked several times during the course of the experiment. A carbon rod with both ends tapered to a blunt point was inserted into the bone chamber cavity which it fitted comfortably. (The pointed end allowed the rod to come in contact with the deepest part of the cavity; the bluntness prevented crumbling of the carbon rod.) The distance from the free end of the inserted carbon rod to the tip of the bone chamber's hemispherical end was measured. The difference between this length and the length of the rod determined the actual thickness of the wall in the hemispherical portion of the chamber. This was checked against the thickness of the walls of the cylindrical portion.

BIBLIOGRAPHY

Bragg, W. H. Studies in Radioactivity. (Macmillan & Co.) 1912.

Fricke, H. and Glasser, O. "A Theoretical and Experimental Study of the Small Ionization Chamber." American Journal of Roentgenology. XIII (1925), 453-461.

Glasser, O. and Rovner, L. "Gamma Ray Measurements in Roentgens." American Journal of Roentgenology. XXXVI (1936), 94-104.

Gray, L. H. "An Ionization Method for the Absolute Measurement of Gamma Ray Energy." Proceedings of the Royal Society of London, Series A. CLVI (1936), 578-596.

Gray, L. H. "Radiation Dosimetry, Part I." British Journal of Radiology. X (1937), 600-612.

Gray, L. H. "Radiation Dosimetry, Part II." British Journal of Radiology. X (1937) 721-742.

Gray, L. H. "The Absorption of Penetrating Radiation." Proceedings of the Royal Society of London, Series A. CXXII (1928), 647-668.

Johns, H., Darby, E., and Kornelsen, R. "Physical Aspects of Treatment of Cancer by 22 Mev X-rays." British Journal of Radiology. XXIV (1951), 355-364.

Mayneord, W. V. "Secondary Electronic Emission from Metal Foils and Animal Tissues." Proceedings of the Royal Society of London, Series A. CXXX (1930), 63-80.

Mayneord, W. V. and Roberts, J. E. "An Attempt at Precision Measurements of Gamma Rays." British Journal of Radiology. X (1937), 365-385.

Spiers, F. W. "Effective Atomic Number and Energy Absorption in Tissues." British Journal of Radiology. XIX (1946), 52-62.

Spiers, F. W. "Dosage in Irradiated Soft Tissue and Bone." British Journal of Radiology. XXIV (1951), 365-368.

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