ABSOLUTE DOSIMETRY
OF
HIGH ENERGY X-RAYS

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CONTENTS

ABSTRACT

1. INTRODUCTION

2. THE STANDARD METHODS OF DOSIMETRY
   2.1 The ionization method
      2.1.1 Energy per ion pair in air
      2.1.2 Relative stopping powers
      2.1.3 Accuracy of ionization measurements
   2.2 The Fricke dosimeter
   2.3 Calorimetric methods
      2.3.1 Intensity measurements
      2.3.2 Measurements of local energy absorption

3. APPARATUS AND TECHNIQUES USED
   3.1 Apparatus for measuring small differences of temperature
   3.2 Thermistors
      3.2.1 Temperature coefficient
      3.2.2 Power sensitivity
   3.3 Sensitivity of the apparatus
   3.4 Carbon ionization chamber

4. MEASUREMENT OF ENERGY ABSORPTION IN WATER
   4.1 Arrangement of the calorimeter
   4.2 Ionization measurements
   4.3 Observed temperature changes
      4.3.1 Effect of heating the glass stem
      4.3.2 Direct effect of radiation on thermistors
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4 Results</td>
<td>84</td>
</tr>
<tr>
<td>4.5 Radiochemical corrections</td>
<td>88</td>
</tr>
<tr>
<td>4.6 Cerenkov radiation and fluorescence</td>
<td>92</td>
</tr>
<tr>
<td>4.7 Discussion of results</td>
<td>94</td>
</tr>
<tr>
<td>5. OTHER ESTIMATES OF THE ABSORBED DOSE IN WATER</td>
<td>97</td>
</tr>
<tr>
<td>5.1 Fricke dosimeter</td>
<td>97</td>
</tr>
<tr>
<td>5.1.1 The polarization correction for the electron beam</td>
<td>102</td>
</tr>
<tr>
<td>5.2 Carbon chamber</td>
<td>105</td>
</tr>
<tr>
<td>5.3 Derivation of W</td>
<td>109</td>
</tr>
<tr>
<td>6. MEASUREMENTS OF ENERGY ABSORPTION IN CARBON</td>
<td>111</td>
</tr>
<tr>
<td>6.1 Construction of the calorimeter</td>
<td>112</td>
</tr>
<tr>
<td>6.2 Heating and cooling conditions</td>
<td>117</td>
</tr>
<tr>
<td>6.3 Deviations from ideal geometry</td>
<td>134</td>
</tr>
<tr>
<td>6.4 Results</td>
<td>140</td>
</tr>
<tr>
<td>6.5 Derivation of W and stopping power values for cobalt</td>
<td>155</td>
</tr>
<tr>
<td>6.6 W and stopping power values for the accelerators</td>
<td>156</td>
</tr>
<tr>
<td>6.6.1 Scattered radiation</td>
<td>156</td>
</tr>
<tr>
<td>6.6.2 X-ray spectra</td>
<td>159</td>
</tr>
<tr>
<td>6.7 Direct calibration of ionisation chambers in terms of absorbed dose from megavoltage radiations</td>
<td>163</td>
</tr>
<tr>
<td>6.8 Measurements at 300 K.V.P.</td>
<td>166</td>
</tr>
<tr>
<td>6.8.1 Corrections</td>
<td>168</td>
</tr>
<tr>
<td>6.8.2 Possible improvements in accuracy</td>
<td>174</td>
</tr>
<tr>
<td>7. CONCLUSIONS</td>
<td>176</td>
</tr>
<tr>
<td>8. REFERENCES</td>
<td>181</td>
</tr>
</tbody>
</table>
The official unit for the measurement of absorbed doses of megavoltage x-rays is the rad, defined as 100 ergs per gramme of the material in question. For this reason, and for comparisons of the relative biological efficiencies of different types of ionizing radiations, there is a requirement for absolute measurements of the energy absorbed from x-ray beams by tissue-like materials.

Existing methods of measurement of absorbed dose are reviewed to indicate their accuracy, the methods considered being ionization in air, the Frick dosimeter and calorimetry.

Energy absorption in water and carbon has been measured by means of an isothermal microcalorimeter, using thermistors to measure the changes of temperature. A pair of thermistors is connected in a wheatstone's bridge and excited at 20 c/s, the out of balance signal being amplified, rectified and displayed on a recording potentiometer. The temperature rise has been compared with the ionization in a carbon chamber exposed in a similar geometry.

Measurements have been made in water using x-rays generated at 8 M.V. and in carbon at several energies of X and
gamma radiation. The measurements in water indicate that the absorbed dose rate is a few per cent less than would be expected from ionization measurements. In carbon the agreement between the two methods is closer. The measurements in carbon have enabled ionization chambers to be calibrated directly in terms of absorbed dose. They have also given some information about the values of the constants to be used in the Bragg-Gray relation for estimating absorbed dose from ionization measurements.
I. INTRODUCTION.

This thesis is concerned with the direct measurement of the absorbed dose in media similar to biological materials, due to irradiation by X and gamma rays.

The recommendation that doses of X and other ionizing radiations absorbed by matter should be specified in absolute terms of energy per unit mass was first made officially in 1953 by the International Commission on Radiological Units (ICRU 1954).

"The absorbed dose of any ionizing radiation is the amount of energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest. It is to be expressed in rads. The rad is the unit of absorbed dose and is 100 ergs per gramme."

The concept of energy absorption as the basis of dosimetry is much older than this. For example Gray et al proposed an energy unit in 1940. This unit was intended specifically for neutrons but would serve for any penetrating radiation, and its value was within a few percent of the rad.
However, before 1953 doses of X and gamma radiation were usually expressed in roentgens, as indeed is still the case in the treatment of patients with X rays up to 3 MeV. The roentgen is a measure of the ionization produced in air, its present definition being -

"The roentgen is an exposure dose of X or gamma radiation such that the associated corpuscular emission per 0.001293 gm of air produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign".

The roentgen is thus a measure of the radiation field to which a specimen might be exposed, rather than a measure of the energy absorbed by the specimen. This led to certain difficulties which were discussed by the International Commission in their report in 1956.

"A measurement in roentgens is a determination of the ionization produced in air under certain conditions; it is not a direct measurement of the intensity of the X- or gamma radiation, of the energy absorbed in air, or of the biological effect, although these quantities may be calculated from the results of such measurements if the pertinent factors are known. Thus it may be difficult to compare directly the
biological effects of X- and gamma rays of different energies measured in roentgens. It is even more difficult to compare the biological effects of X- or gamma rays measured in roentgens with the effects of other radiations (or particles) measured in different units."

Specification of absorbed doses in terms of the energy absorbed per gm represents a common basis for the measurement of all types of ionizing radiations.

Another reason for the introduction of the new unit in 1953 was the difficulty of making measurements in roentgens for X rays of very high energy (above about 3 MeV). At about this time a number of generators working in the range 4 - 30 MeV were being brought into use for radiotherapy. At these energies the range of the associated corpuscular emission becomes comparable with the mean free path of the quanta. An air-filled cavity in which the ionization is being measured must therefore be surrounded by a wall of material which is equivalent to air in terms of its emission and absorption of ionizing corpuscles, and which is thick enough to make a full contribution and to exclude any corpuscles from outside. Such a thick wall significantly attenuates the X radiation. There is then some doubt as to the correction to be applied for this attenuation, and also
as to the point in space at which the radiation field is being measured.

Nevertheless the standard method of estimating absorbed doses in rods is by means of a measurement of the ionization in air. This is partly because the method has been in use for many years, and has been refined to a high degree of reliability. Partly it is because of the technical difficulties of a direct measurement of absorbed energy; for example in radiotherapy a normal daily exposure dose of X rays of 200 rontgens causes a rise in temperature of only $7 \times 10^{-4}$°C in the irradiated tissue.

It is the aim of the present work to make direct measurements of energy absorption in tissue-like materials, and to correlate them with measurements of ionization in air under normal conditions.

2. The Standard Methods of Dosimetry.

As stated above, the usual method of dosimetry is by a measurement of the ionization in air. Other primary methods that have been used are the Fricke Dosimeter, and calorimetry. Other dosimeters, for example those depending on the colouration of plastics and glasses, are secondary instruments, in that their sensitivities have been found
empirically by comparison with primary dosimeters.

To assess the need for calorimetric measurements a brief review will be made of the three primary methods. 2.1. The Ionization Method.

There are two ways of using the ionization method, namely by employing a free air chamber or a cavity chamber.

A free air chamber measures the exposure in rontgens, and thimble chambers can be calibrated against it to measure the exposure dose received by a biological specimen. Knowing the exposure dose, the absorbed dose in air depends only on the average energy needed to produce one ion pair, usually denoted by $W$. The state of present knowledge of this quantity is discussed in Section 2.1.1. Under conditions of electronic equilibrium the absorbed dose in the biological material is equal to the absorbed dose in air multiplied by the ratio of the energy absorption coefficients. By energy absorption coefficient is meant that part of the total absorption coefficient corresponding to energy

\[ \text{since this review was written a fresh report of the ICRU has appeared (NBS handbook 78, 1959). It contains much of the information quoted here, but includes little fresh fundamental data beyond that given in the previous report, handbook 62.} \]
locally absorbed. A table of values is given in NBS handbook 62, and fig. 1 of this thesis shows the absorbed dose in water per roentgen, plotted against quantum energy. There is a variation of 10% between 50 kev and 120 kev. This variation shows that in this energy region it is necessary to know the spectrum of the radiation. Owing to scattering in extended media the spectrum at the point of interest is seldom known accurately, and errors of a few percent can easily arise from this cause. Other materials of course show different variations, but soft tissue is not very different from water.

The use of a free air chamber becomes more difficult at higher X ray energies since the large plate spacing required to accommodate energetic recoil electrons leads to difficulties with saturation and with the inclusion of ionization due to scattered photons. In Great Britain the free air chamber at the NPL will operate only with X rays up to 300 kV (Smith, 1955). A chamber working at high pressure has been successfully used in the United States for measuring the exposure dose from Cobalt - 60 gamma rays (Wyckoff 1960). The accuracy obtained was estimated to be about the same as that using cavity chambers. However, the use of this free air chamber presents many difficulties, and during the next few years the dosimetry of energetic X radiation will continue to be based on cavity
FIG. 1

ENERGY ABSORPTION per GM of WATER per RONTGEN
(W = 34)

ERGS/GM

QUANTUM ENERGY

12 KeV

100 KeV

1 MeV
chambers. The free air chamber, then, enables the measurement of absorbed doses from X rays generated at 300 kVp or below to be made with an accuracy which, under the best conditions, is limited only by the accuracy with which \( W \) is known, namely about \( \pm 1.5\% \).

The use of cavity chambers to measure absorbed doses is based on application of the Bragg-Gray principle. This requires the cavity to be small enough that 1) a negligible proportion of the energy of the recoil electrons is dissipated in it, 2) a negligible fraction of the ionization is due to recoil electrons arising in the gas in the cavity, and 3) the X ray intensity is constant over the volume of the chamber. The energy absorption in the wall can then be deduced from the ionization in the gas by the relation

\[
E = J W S_m - - - - - (1)
\]

where \( E \) is the energy absorption per gm of gas

\( W \) is the average energy to form one ion-pair in the gas

\( S_m \) is the average relative mass stopping power of wall to gas, for the recoil electrons,

\( J \) is the ionization per gm of gas.

This relation is based on the fact that the presence of a small cavity does not alter the distribution of recoil electrons. The accuracy of the method thus depends on the accuracy with which the quantities \( W \) and \( S \) are known.
It is in theory still possible to measure exposure doses with a cavity chamber, by making the wall out of material having an atomic constitution similar to that of air. In this case it is not necessary for the cavity to be so small (Fano 1954). However, the mass stopping power of a medium is slightly dependent on the density, particularly for high energy electrons, so that this method does not avoid the necessity for knowledge of stopping power ratios.

2.1.1. Energy per ion pair in air.

It has not yet been possible to calculate the value of \( W \) for air with sufficient accuracy (Bethe and Ashkin, 1953, Fano 1946).

A large number of experimental determinations have been made, for various gases and ionizing radiations, but only those of ionization of air by electrons are of direct interest here. Recently reviews have been made by Emery (1956), Weiss and Bernstein (1957), Valentine and Curran (1958) and Boeg (1958). There has been little fresh information since Boeg's review. The more recent and reliable measurements are given in Table 1. The results range from 33.5 to 34.3 e-v per ion pair, the mean being 33.8, and it seems likely that the true value of \( W \) lies between 33.5 and 34 e-v per ion pair. This is significantly different from the value of 32.5 which was in
general use up to about 1956 (see for example Hine and Brownell (1956, page 37).

The lack of variation of $W$ with energy of the electrons is a remarkable feature of these measurements, and one which makes the Bragg-Gray relation easier to apply. At sufficiently low energies the value of $W$ must rise, since electrons with energy less than the ionization potential of the gas must lose energy without causing any ionization. But this effect has not been significant in any of the recent measurements. Jesse and Sadauskis (1955, 1957) compared measurements with $^3$H, $^{63}$Ni, and $^{14}$C having average $\beta$ ray energies of about 4, 17 and 50 Kev, and could find no significant variation of $W$ in this energy range. Further, their values agree with those of others using much more energetic electrons, as shown in Table 1.

2.1.2. Relative Stopping Powers.

The quantity $S_m$ in the Bragg-Gray equation is the ratio of the mass stopping power of the wall material to that of the gas for the recoil electrons, averaged over their energy distribution.

For monoenergetic electrons the stopping power of any material can be found from Bethe's formula (Bethe and Ashkin, 1953).
TABLE I.
Recent Measurements of Air for Electrons.

<table>
<thead>
<tr>
<th>Author</th>
<th>Radiation</th>
<th>Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Ovadia et al 1955</td>
<td>9-17.5 Mev electrons</td>
<td>34.3 ± 1.0</td>
<td>Ion pairs per cm measured. Energy loss per cm theoretical.</td>
</tr>
<tr>
<td>b) Barber 1955</td>
<td>1-34 Mev electrons</td>
<td>33.8 ± 1.2</td>
<td>As A). Measured in N2, H2, He. Figures of Jesse and Sadauskis (1957) used to convert to air. See also Bernier et al (1956), Table 7.</td>
</tr>
<tr>
<td>c) Weiss, Bernstein 1955</td>
<td>2 Mev. X rays</td>
<td>33.9 ± 0.8</td>
<td>Ionization chamber. Energy in wall by Fricke dosimeter, assuming G = 15.45.</td>
</tr>
<tr>
<td>d) Emery 1956</td>
<td>Various isotopes</td>
<td>about 33.5</td>
<td>Ionization chambers with isotopes incorporated in the walls. Energy by measured disintegration rate and theoretical energy per disintegration. Assumes standard output of radium = 8.3 r/hr.</td>
</tr>
<tr>
<td>e) Gross, Wingate, Failla 1957</td>
<td>35β rays (about 50 Kev)</td>
<td>33.6 ± 0.3</td>
<td>Ionization chamber with Isotope incorporated in wall. Energy by microcalorimetry of source.</td>
</tr>
<tr>
<td>f) Bay et al 1957</td>
<td>35β rays</td>
<td>33.7 ± 0.3</td>
<td>Total ionization measured, energy by microcalorimetry.</td>
</tr>
<tr>
<td>Author</td>
<td>Radiation</td>
<td>Result</td>
<td>Remarks</td>
</tr>
<tr>
<td>----------</td>
<td>------------</td>
<td>----------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>g) Jesse 1958</td>
<td>$35S$ $\beta$ rays</td>
<td>$33.9 \pm 0.7$</td>
<td>Ionization and disintegration rate measured. Mean electron energy theoretical.</td>
</tr>
<tr>
<td>h) Goodwin 1959</td>
<td>$^{137}$Cs $\gamma$ rays</td>
<td>$33.9 \pm 0.5$</td>
<td>Ionization chamber. Energy in wall from calorimetric measurement of beam intensity, and theoretical absorption coefficients.</td>
</tr>
<tr>
<td>i) Reid and Johns 1961</td>
<td>$^{60}$Co and $^{137}$Cs $\gamma$ rays</td>
<td>$33.8 \pm 0.4$</td>
<td>C and Al ionization chambers. Energy in wall by calorimetry.</td>
</tr>
</tbody>
</table>

Note. In g), e), h) and i) the product $WS$ was in fact measured, and stopping power values were calculated to derive $W$. The same is really true in the case of d) since the figure for the standard output of radium involves assumptions of stopping power values.
\[- \frac{dE}{dx} = \frac{2\pi Ne^4}{m v^2} \left\{ \ln \frac{m v^2 E}{2 \pi^2 (r \beta^2)} - \ln 2 (2 \sqrt{1 - \beta^2} + 1 - \beta^2) + 1 - \beta^2 \right\} - 8 \delta \]

The quantity \( \delta \) represents the polarization correction. Otherwise the only unknown quantity is \( I \), the mean excitation potential of the atoms. This cannot be calculated accurately, and is estimated from measurements of energy loss of heavy particles where losses due to scattering are small. The value of \( I \) so found should be independent of the energy of the particle.

The correction term \( \delta \) allows for polarization of a condensed medium. It will be discussed in more detail later, but it must be pointed out now that it contains two components (Sternheimer 1954, Whyte 1959) one independent of energy (called the Zero Energy effect) and the other varying with energy but only significant for electrons above 1 Mev. The symbol \( \delta \) represents only the variable energy component; the zero energy component implies that a material in the vapour phase should have a slightly greater mass stopping power at low energies than in the liquid or solid phase, the difference being expected to be about 1 or 2\%. This component is included in the experimentally determined value of \( I \) when solids are used.
There is considerable uncertainty about the proper values of $I$ to use in this equation. For example the report of the ICRU (1956) used $I = 13Z$, following Caldwell (1955). Cormack and Johns (1954) used $I = 13.5Z$. For air these assumptions give mean values of $I$ of 94.5 and 98.2 ev. On the other hand the value determined experimentally by Bethe (1937) is 80.5. Bethe's figure leads to a stopping power of air (to 0.5 MeV electrons) 1.6% greater than the ICRU figure. Some of this difference may be due to the zero energy density effect, but similar difficulties occur for other materials of interest in dosimetry. For example for Aluminium Mather and Segrè (1951) found $I = 148$ while Caldwell (1955), reviewing other work, estimated a mean value of 163.

In the circumstances there has recently been a considerable amount of fresh experimental work and of reinterpretation of older data, in particular by applying better corrections for the reduced efficiency of bound electrons in stopping relatively slow particles. Much of this was discussed at a conference at Gatlinburg in September 1958. Unfortunately no comprehensive report on the results of this conference has yet been published, although a draft report has been made by Attix et al. (undated) for the U.S. National Committee on Radiation Protection and Measurement.
Attix et al. have recalculated $I$ for air from Bethe's measurements, using fresh data and corrections by Wilske (1952), and find $I = 85 \text{ e-v}$. They also find $I = 85 \text{ e-v}$ from measurements made in gases by Brolley and Ribe (1955).

The most important solids for X-ray dosimetry are carbon and aluminium. Attix et al. consider that 164 e-v is the best figure for aluminium and have normalised the results of Bakker and Segre (1951) accordingly. Their normalised figures for carbon are then 84 e-v from Bakker and Segre and 78.4 from Thompson (1952). Both these were measurements in solids. Brolley and Ribe's measurements in gases (including hydrocarbons) give $I$ (carbon) = 67; this smaller figure may be due to the zero energy density effect.

Some values of $I$ recommended by Attix et al. are compared with those of the ICRU (1956) in Table 2. Except for air they are all for solids and liquids.

<table>
<thead>
<tr>
<th>Element</th>
<th>H</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>Al</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I$ (e-v) according to (Attix et al)</td>
<td>20.7</td>
<td>78.4</td>
<td>85.1</td>
<td>98.3</td>
<td>164</td>
<td>85.0</td>
</tr>
<tr>
<td>(ICRU)</td>
<td>13</td>
<td>78</td>
<td>91</td>
<td>104</td>
<td>169</td>
<td>94.5</td>
</tr>
</tbody>
</table>
The main uncertainty is the ionization potential of air. When using either of these sets of figures the uncertainty in the relative stopping power of one of the solids to air may be as high as 2\%.

In chemical compounds the stopping power is not quite equal to the sum of the atomic stopping powers of the constituents. This has been studied by Thompson (1952) and Brandt (1956), who found variations of a few percent. However, they showed that by ascribing different values of $I$ depending on the type of bond, stopping powers could be predicted to closer than 1\%. In any case most fundamental dosimetric work is done with pure elements, but if an attempt is made to match the chemical composition of the wall and gas of an ionization chamber, it must be remembered that the relative stopping power may be slightly different from unity due to this effect (in addition to that of the zero energy density effect).

The polarization correction term $\delta$ represents the screening of more distant parts by polarization of the medium close to the track of the particle. This effect increases with the density of the material and is often called the density effect. In the case of relativistic particles the Lorentz contraction of the electric field of
the moving particle makes distant interactions more important at higher energies. The effect was discussed by Fermi in 1940, and detailed calculations have been made by Sternheimer (1952, 1953, 1954, 1956). In carbon it amounts to 2.6% at 1 MeV and 12% at 10 MeV.

Experimental measurements of the effect have been made by Whyte (1957), Skarsgard et al (1957), Zsula et al (1957), Hudson (1957), Goldwasser et al (1955) and Barber (1956). The approximate magnitude of the effect for 8 MeV electrons in water has also been measured in the present work (section 5.1.1). All these measurements have confirmed the accuracy of Sternheimer's calculations, often to an accuracy of the order of 1%.

The discussion so far has been concerned solely with electrons of a single energy. In practice recoil electrons are produced over a wide range of energies and are then slowed down by the medium. The relative stopping power factor varies slightly with the electron energy, and an effective mean value must be found.

It has usually been assumed (for example ICRU (1956)) that the electrons are continuously slowed down in the medium, in infinitesimal steps, so that the flux at any energy is inversely proportional to the stopping power. Following Spencer and Attix (1955), let electrons
be generated with initial energy $T_0$ throughout the medium. As they are slowed down there is a flux $dn$ having energies between $T$ and $(T + dT)$ crossing the cavity and surrounding medium. The flux is related to the stopping power by

$$dn \frac{S_{z}}{S_{z}^{\text{tot}}} = KdT$$

where $S_{z}^{\text{tot}}$ is the total mass stopping power of the medium, including radiation losses. The effect of radiation losses is to reduce slightly the flux of energetic electrons while increasing slightly the flux of low energy quanta. Putting $S_a^{\text{coll}}, S_z^{\text{coll}}$ equal to the collision parts of the mass stopping powers of air and the medium, the energy absorption per gm of air and medium are given by

$$dE_a = S_a^{\text{coll}}dn = S_a^{\text{coll}} KdT / S_{z}^{\text{tot}}$$

$$dE_z = S_z^{\text{coll}}dn = S_z^{\text{coll}} KdT / S_{z}^{\text{tot}}$$

Writing $E_z = JWS (T_0)$ for the total energy absorption and ionization due to these electrons,

$$\overline{S} (T_0) = E_z / E_a = \int_{0}^{T_0} \frac{S_z^{\text{coll}}}{S_{z}^{\text{tot}}} dT / \int_{0}^{T_0} \frac{S_a^{\text{coll}}}{S_{z}^{\text{tot}}} dT$$

$$\overline{S} (T_0) = E_z / E_a = \int_{0}^{T_0} \frac{S_z^{\text{coll}}}{S_{z}^{\text{tot}}} dT / \int_{0}^{T_0} \frac{S_a^{\text{coll}}}{S_{z}^{\text{tot}}} dT$$
If radiation losses are neglected this reduces to

\[
\overline{S}(T_0) = T_0 \int_0^{T_0} \frac{S_a}{S_c} dT
\]

(5)

The effect of radiation losses in the case of carbon has been estimated using the approximation \(S^\text{rad}/S^\text{coll} \approx E_2/1600 \text{mc}^2\).

At \(T_0 = 14 \text{ MeV}\) equation (4) then gives the same result as (5), to 0.1%. Evidently radiation losses can be neglected.

This value of \(\overline{S}(T_0)\) must now be integrated over the spectrum of initial energies of the recoil electrons. Let this be given by \(A(T_0) dT_0\). Writing \(E_Z = \overline{W} \overline{S}_m\) for the total spectrum,

\[
\overline{S}_m = \frac{E_Z}{E_A}
\]

and \(dE_Z = T_0 A(T_0) dT_0\)

also \(dE_A = dE_Z/\overline{S}(T_0)\)

Therefore

\[
\overline{S}_m = \int_0^{T_{\text{max}}} A(T_0) dT_0 \int_0^{T_{\text{max}}} \frac{T_0 A(T_0)}{\overline{S}(T_0)} dT_0
\]

(6)

The spectrum of initial electrons should include those formed by absorption of bremsstrahlung due to radiation losses in other parts of the medium. However, in the case of carbon this correction is likely to be very small and has been neglected. Values of \(S_a/S_c\) and \(1/\overline{S}(T_0)\) are
shown in Fig. 2. These include the polarization correction as calculated by Nelms (1958). $S_a/S_c$ decreases steadily as the energy falls and a cut-off has been used at 10 KeV in the integral for deriving $1/\bar{S}(T_o)$; an electron of this energy has a range of only 2.2 mm in air at S.T.P.

A factor which has been neglected so far is the effect of delta rays. This has been considered by Spencer and Attix (1955) and Burch (1955). These writers consider energetic delta rays as additions to the electron spectrum, but delta rays with less than a critical energy are regarded as a form of local ionization and are not added to the spectrum. The critical energy is of the order of the energy needed to cross the cavity, and so varies with chamber size and gas pressure. As a result the ionization per unit mass of gas and hence the proper value of $\bar{S}m$ is a function of chamber size.

The predictions of these theories have been tested by Whyte (1957), Greenwood (1957), Attix and Ritz (1957), Attix De la Vergne and Ritz (1958), Cormack and Johns (1954) and Burlin (private communication, to be published). The calculations of Burch do not allow of such extensive
checking as those of Spencer and Attix, but his calculation for a 2cm diameter graphite chamber predicts that the ionization should be 0.6\% greater than would be expected when delta rays are neglected. This is not borne out by any of the experiments, all of which (with the exception of Cormack and Johns) are in general agreement with the theory of Spencer and Attix. In the case of graphite the effect is very small; for a chamber of 1mm or more in dimensions the correction to be introduced is only a few tenths of a percent. On the other hand, for an aluminium chamber with a one millimetre gap Spencer and Attix predict a correction of 2 or 3 percent.

Summarizing the problem of stopping powers, the principal uncertainty arises from the proper value of the mean excitation potential I, which may lead to an uncertainty of 2\% in relative stopping power. It might be prudent to allow an uncertainty of 1.5\% in the estimate of the polarization correction above 1 MeV. Provided a graphite chamber is used the effect of chemical combination is zero (using a value of I measured with graphite), and the effect of delta rays is small.
2.1.3. Accuracy of Ionization Measurements.

The uncertainties quoted above are upper limits, giving say 95% confidence. Taking \( H = 33.8 \pm 0.3 \), or 1%, also to a 95% confidence level, then the mean square value of the uncertainty is \( (2^2 + 1^2 + 1^2)^{1/2} < 2.5\% \). In other words one can be reasonably confident that the ionization method is capable of an accuracy of 2.5%. This figure of course does not include any errors involved in the practical use of ionization chambers, such as saturation, the measurement of charge, the effect of water vapour, and the effect of a finite cavity and its walls on the flux of electromagnetic radiation. However, in careful work each of these errors can often be kept well below 1%. To estimate the absorbed dose in a biological material, the result of using the ionization chamber must be multiplied by the ratio of the true absorption coefficient of the material in question to that of the wall material of the chamber. In the energy range where only the Compton effect is important this process will not introduce any further appreciable error.
2.2. The Fricke Dosimeter.

The use of radiochemical reactions is a second primary method of X ray dosimetry because the radiochemical yield per unit of energy absorbed can be measured without the use of ionization chambers. The system on which by far the greatest amount of accurate work has been done is the oxidation of ferrous sulphate in acid solution, first described by Fricke and Morse (1927). The usual concentration of reagents is $10^{-3}$ Molar ferrous ammonium sulphate in 0.8 or 0.1 Normal $H_2SO_4$. The concentration of ferric ion formed by the radiation is conveniently estimated with a spectrophotometer. The useful range lies between $2 \times 10^3$ and $4 \times 10^4$ rads, the lower limit being set by the performance of normal spectrophotometers and the upper one by depletion of oxygen in the solution, the yield being reduced when oxygen is not present. The yield is independent of dose-rate up to at least $10^6$ rads/sec (Sutton and Rotblat (1957), Schuler and Allen (1956)). A practical difficulty is that the yield can be drastically altered by traces of impurity in the solution. This can be detected by the addition of Chloride ion which has no effect on the yield in the absence of impurities but alters the yield when impurities are present.
Table 3 gives the results of recent measurements of yield in which ionization chambers were not used.

Table 3.

Yield of Fricke dosimeter in 0.8 N acid.

<table>
<thead>
<tr>
<th>Number</th>
<th>Reference</th>
<th>Type of radiation</th>
<th>Approximate mean initial electron energy Kev</th>
<th>Method of energy measurement</th>
<th>Value of extinction coefficient used (At 20°C)</th>
<th>$G(Fe^2+)$ atmo oxidised per 100 e-v.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Soldick and Allen (1954)</td>
<td>Electrons</td>
<td>2,000</td>
<td>Fonor input</td>
<td>2188</td>
<td>15.6±5</td>
</tr>
<tr>
<td>2.</td>
<td>Schuler and Allen (1955)</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2118±6</td>
<td>15.45±16</td>
</tr>
<tr>
<td>3.</td>
<td>Hochadel and Ghormley (1953)</td>
<td>Cobalt</td>
<td>500</td>
<td>Colorimetry</td>
<td>2162</td>
<td>15.6±3</td>
</tr>
<tr>
<td>4.</td>
<td>Lazo, Dewhurst and Burton (1954)</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2122±10</td>
<td>15.8±3</td>
</tr>
<tr>
<td>5.</td>
<td>Donaldson and Miller (1955)</td>
<td>$^{32}$P Electrons</td>
<td>690</td>
<td>Absolute Counting</td>
<td>2150</td>
<td>15.4±8</td>
</tr>
<tr>
<td>6.</td>
<td>Peisach and Steyn (1960)</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>?</td>
<td>15.3±13</td>
</tr>
<tr>
<td>7.</td>
<td>McDonell and Hart (1954)</td>
<td>$^3$H Electrons</td>
<td>5.7</td>
<td>&quot;</td>
<td>2227</td>
<td>12.9±2</td>
</tr>
</tbody>
</table>
Note - x Temperature not given. In the other cases the stated extinction coefficient has been corrected to $20^\circ\text{C}$ by allowing for an increase of 0.7% per deg C.

Numbers 2 and 4 are repeats of 1 and 2 respectively, under improved conditions. 7 used very low energy electrons, and under these conditions the yield is known to be reduced. 6 does not agree too well with 4 but the extinction coefficient is not stated. (Actually the results of 6 are stated to be $G = 15.39 \pm 0.04$ by $4\pi$ proportional counting and $15.21 \pm 0.04$ by $4\pi$ liquid scintillation counting). The extinction coefficients in 2 and 4 agree well with the recent figure of 2124±4 found by Henderson and Miller (1960). The best final result for energetic X rays (i.e. those generated at over 500 KVP) is probably $G \pm 15.6 \pm 0.2$ (standard error), giving 95% confidence that the true yield is within 2.5% of this figure. Thus the Fricke dosimeter is capable of about the same accuracy as ionization chambers in the measurement of absorbed doses from energetic X rays.

2.3 Calorimetric Methods.

Microcalorimeters have been applied to X ray dosimetry in two ways. They have been used to measure the intensity of a beam of radiation, by measurement of the temperature
rise of a block of lead in which the beam is totally absorbed. They have also been used to measure directly the energy locally absorbed in materials of low atomic number, from which the energy absorption in biological materials can easily be inferred. The experimental work reported in this thesis is an example of the second application.

2.3.1. Intensity Measurements.

Although a measurement of the intensity of an X or gamma ray beam gives less direct information about the absorbed dose in biological materials, this method has been used more frequently than the second type. Such measurements have been reported by Genna and Laughlin (1955), Laughlin et al (1953), Dolphin and Innes (1956), Zendle et al (1956), McElhinney et al (1957) and Goodwin (1959). In these measurements a collimated beam of accurately known area was absorbed in a lead block, small corrections being applied for the energy backscattered and transmitted. Exact measurement of the area of the beam is one of the main sources of uncertainty in these measurements. The energy absorbed in the lead block was measured by means of thermistors, and a heating coil was also embedded
in the block to give an absolute calibration. The measured intensity has usually been compared with the ionization in a chamber placed in the same collimated beam.

At low energies the chamber can be calibrated against a free air chamber. If the exposure dose rate is R rontgens per second, and the measured intensity is I, then \[ I \left( \frac{\mu a}{\rho} \right)_{\text{air}} = WR \] in the appropriate units. The real absorption coefficient of air, \( (\mu a/\rho)_{\text{air}} \), varies with energy and an accurate knowledge of the spectrum of radiation is necessary if a value of \( W \) is to be derived.

Alternatively a cavity chamber may be used. In this case the energy absorption in the wall is given by

\[ E = J \alpha S \]

for ionization

and \[ E = \frac{\mu a}{\rho} It \]

where \( \mu a/\rho \) is the real mass absorption coefficient of the wall material. A value of \( WS \) may be found by combining these two equations, but again \( \mu a/\rho \) varies with energy.

The method therefore is most useful in the case of monochromatic radiation from radioactive sources such as \( ^{60}\text{Co} \) and \( ^{137}\text{Cs} \), although even in these cases some allowance has to be made for the presence of degraded
The accuracy obtained by Glenna and Laughlin (1955) and Goodwin (1959) was about 1.5% (standard error) in the measurement of intensity, leading to an estimate of $W_S$ with a standard error of about 2%. Actually Goodwin gives his result as a value of $W$ alone, but his "air-walled" chamber was calibrated against a carbon chamber so that a value of $S$ for carbon to air must have been assumed but is not given in his paper.

An interesting variant of this method was used by Adams (1957) who measured the intensity of the X ray beam from a 70 MeV synchrotron before and after passing it through a large tank of water. The energy absorption in the water was given by the difference between these measurements, and was related to the ionization integrated throughout the water, and ultimately to the ionization in an extrapolation chamber of unspecified construction. Adams estimated an accuracy of 5%, mainly due to difficulties in the integration. There seem to have been at least two systematic errors for which no allowance was made. Some radiation outside the main beam, either penetrating the diaphragms or scattered from them, would contribute to the ionization in the water tank without being intercepted by the lead absorber in the calorimeter. No information is
given whereby the importance of this correction can be estimated. The other systematic error lies in the loss of fast electrons from the back of the water tank, most of which were probably not intercepted by the lead absorber. This loss of ionization can be estimated from the build-up curve at the front, which represents loss of ionization that would occur due to recoil electrons from an additional layer of water added to the front. In this way I estimate the correction to be about 2%.

A similar principle was used by Zimmer (1954), who measured the energy absorption in water per rontgen due to Cobalt gamma rays. He used a cobalt source of known strength (determined by counting methods). The source was placed in a large tank of water and the integrated ionization was estimated using "air-walled" chambers. Zimmer estimated that one roentgen delivered an absorbed dose of 84 ergs per gramme of water, while the theoretical figure (taking W = 33.5 ev/impair) is 96. It seems that this type of measurement, involving integration of ionization over large volumes of water in which the photon spectrum is changing, is liable to involve serious errors.

A similar principle was used by Gray (1937), who measured the integrated ionization in cavities throughout a large block of aluminium when a radium source was placed at
the centre. Using a measured value for the relative stopping power of aluminium to air, and assuming \( W = 32.5 \), he estimated the energy output of radium to be 8.31 cals per gm per hour. Zlotowski's (1935) measured figure (corrected by Gray) was 8.9. To bring Gray's result up to this, it would be necessary to put \( W = 34.8 \) e-v per ion pair.

2.3.2. Measurement of Local Energy Absorption.

In comparison with the methods described so far, measurement of energy locally absorbed in tissue-like materials is a direct method of measuring absorbed dose. Owing to the elaborate apparatus needed, the method is only suitable for calibrating secondary instruments such as ionization chambers.

An early attempt at measuring energy absorption in a liquid was made by Stahel (Stahel 1929, Murdoch and Stahel 1935), but only poor accuracy could be achieved. Recently a number of measurements have been reported. Milvy, Genna, Barr and Laughlin (1958) measured the energy absorption in tissue equivalent plastic when irradiated by \( ^{60}\text{Co} \) gamma rays, and compared it with the yield of the Fricke dosimeter irradiated under similar conditions. A difference of 2.3% was attributed to endothermic chemical reactions due to the radiation. Boag, Dolphin and Rotblat (1958),.
using 14 MeV electrons, calibrated perspex dosimeters by a calorimetric method. Hart et al (1958) used a spherical carbon calorimeter irradiated with $^{60}$Co and compared the energy absorption with the ionization in a spherical carbon chamber. The report is of a preliminary nature. Goodwin (1960) measured the energy absorption in thin layers of perspex, aluminium and tissue equivalent plastic using X rays in the range 1.1 - 3.2 mm Cu h.v.l. These measurements were intended to demonstrate the increased energy absorption per roentgen in bone at softer qualities. They would not be suitable for an estimate of W unless the spectrum of radiation were known accurately. A Canadian group (Skarsgard et al 1957, Bernier et al 1956 and Reid and Johns 1961) measured the energy absorption and ionization in small cylinders of carbon and aluminium when irradiated by $^{60}$Co and $^{137}$Cs gamma rays and X rays generated at 22 M.V.

In the latest paper, Reid and Johns have used a more accurate method than that reported earlier. The energy was absorbed in discs 3cm diameter and thickness 0.5, 1.0 and 1.5 gm/cm$^2$. The discs were surrounded by a baffle of the same material to provide electronic equilibrium. Ionization measurements were
made in small cylindrical chambers of the same materials. Corrections were applied to allow for attenuation of the radiation in the chamber walls and in the material of the absorber, and also for scatter from the stem of the chamber. This work is similar to some of that reported in this thesis and will be discussed further in Section 6.

3. APPARATUS AND TECHNIQUES USED.

Starting at this section, the thesis will be concerned with my experimental measurements of energy absorption in water and carbon.

Two samples of the material (sometimes 4) were placed in a metal calorimeter box maintained at a constant temperature, and a thermistor was embedded in each. Only one was irradiated at a time, the other serving as a control. The technical problem was to measure the very small difference of temperature arising between the samples as a result of the irradiation. A typical figure is that a difference of $10^{-3}$ °C would be produced by one minute's irradiation.

The details of the calorimeter were different when water and carbon were used, and they will be discussed in Sections 4 and 5. This section will be concerned with the apparatus common to both materials, namely the apparatus for measuring the small temperature differences, the thermistors, and the carbon ionization chamber with which the absolute measurements of ionization were made.
3.1. Apparatus for Measuring Small Differences of Temperature.

An apparatus for measuring small temperature differences was needed which would be robust and moveable. The use of thermocouples requires a galvanometer amplifier of high gain. This is a disadvantage since the apparatus is sensitive to vibration. Thermistors can be used in a Wheatstone's bridge network, and the use of a galvanometer to detect the out-of-balance voltage can be avoided by using a vibrating-reed amplifier. However, it is best to reverse the polarity frequently to avoid errors due to thermo-electric potentials, and an AC bridge using a tuned amplifier as detector seemed likely to be the most sensitive possible method. High resistance thermistors (100k at room temperature) were used to give the maximum voltage sensitivity for a given power dissipation. The use of an AC bridge to achieve the maximum possible sensitivity has not previously been reported.

A possible source of difficulty using AC lies in the stray capacitances, both between different points on the Wheatstone's bridge and between various points and earth. To minimise this a very low frequency of 20 c/s was used. In practice it was found that the principal source of noise was flicker noise in the first valve of the detector, and a higher frequency might have been an improvement.
FIG. 3. MICROCALORIMETER — BLOCK DIAGRAM

Valve Voltmeter

Oscillator

Phase Splitter

Thermistor Bridge

Detector Amplifier

Filter

Amplifier

Synchronous Rectifier

Oscilloscope

Recording Potentiometer
Fig. 4 Preamplifier.

All values in MΩ and µF.
Fig. 3 is a block diagram of the equipment. Starting from the left hand side, the signal from an A.F. Oscillator (Ediswan) drives a phase splitter. This is a single valve with balanced anode and cathode loads, and provides a signal which is accurately split about earth potential. The output of the oscillator can be measured by a valve voltmeter, in which the alternating voltage is rectified and balanced against a standard cell. No point on the bridge is earthed. The detector is a push-pull amplifier which discriminates against signals having the same phase on both inputs; its circuit is given in Fig. 4. The effects of some of the stray capacitances to earth are eliminated in this way. An alternative method is to earth one of the two output points of the bridge and to detect the signal on the other. This method cannot achieve so great a sensitivity. The effects of stray capacitances to earth are much more difficult to eliminate. Also the phase splitter stage then forms part of the bridge network, as can be seen from the equivalent circuit in Fig. 5. Here 4 resistors R represent the thermistor bridge, and a change in one of the load resistors R' of the phase splitter will affect the output voltage. With the circuit actually used no difficulty was found in balancing the bridge to better than one part in 10⁶.
Following the bridge there is a filter unit, consisting of a push-pull feedback amplifier using a Wien bridge in the feedback loop; its frequency response is shown in Fig. 6. When the filter was more sharply tuned there was a tendency for ringing to occur following electrical transients, and the performance of the equipment was not improved. The waveform can be observed on a cathode-ray tube, the amplifiers of which are used for further amplification following the filter. The final signal is synchronously rectified by means of a Carpenter polarized relay (Telephone Manufacturing Co.). The moving contact is made to vibrate by using another signal from the oscillator (see Fig. 7). The rectifier is thus sensitive only to signals of the proper frequency. Also the phase of the vibrations can be adjusted by altering the 100K variable resistor, and in this way the rectifier can be made to reject signals arising when the bridge is reactively out of balance. H.T. supplies are stabilized with simple neon-valve circuits, and the AC supply is via a mains stabilizer (Servomex).
Fig. 7. Synchronous Rectifier
In Fig. 3 the thermistor bridge is shown as two thermistors and two 100K resistors, with a balancing resistor which is a decade resistance box. The two 100K resistors are constantan coils and were mounted side by side in a junction box. The junction box was joined by short cables to the thermistors in the calorimeter. These two units and the detector amplifier were in the treatment room during irradiations, the rest of the apparatus (including the decade resistance box) being in the control room. The detailed circuit of the bridge varied somewhat from time to time, but a typical arrangement is shown in Fig. 8. The 3 position switch selects one of 2 pairs of thermistors, and in position 3 the resistance of one thermistor alone can be measured, by bringing an additional 100K resistor into the circuit. This enables the temperature inside the calorimeter to be measured.

Fig. 9 is a photograph of the whole apparatus. The rack contains all the electronics except for the synchronous rectifier which is the box on top of the recording potentiometer. The apparatus is shown connected to the carbon calorimeter, which is enclosed in celotex boards on the left hand side. The edge of the vacuum pump used for evacuating the calorimeter can just be seen. In front is a potentiometer and associated apparatus for putting known amounts of electrical energy into the calorimeter.
Fig. 8. Bridge Junction Box.
3.2. Thermistors.

The thermistors were supplied by Standard Telephones and Cables. For measurements in water type F was used, in which the element is a very small bead sealed into the end of a glass tube. For measurements in carbon type M was used. Here the element is sealed into a thin layer of glass which is stuck onto a copper disc. For these measurements it was prised off the copper disc and stuck with Araldite onto a piece of carbon. The thermistors are shown in Fig. 10.

3.2.1. Temperature Coefficient.

The resistance of a thermistor decreases with rising temperature, the relation being given by the manufacturers as

\[ R = \frac{a}{e^{b/\theta}} \]

where \(a\) and \(b\) are constants and \(\theta\) is the absolute temperature.

The exact value of the temperature coefficient is not needed for the measurements in carbon, since an energy calibration could be made electrically. But in water the estimate of energy absorption depends directly on the temperature coefficient of the thermistor.

This was measured in a water bath. A type F thermistor projecting from the end of a polythene tube was attached to a
Type M

1 cm.

Type F
mercury in glass thermometer with graduations every hundredth of a degree, the tip of the thermistor being at the same level as the bulb of the thermometer and about 30 cm below the surface of the water. The water bath was vigorously stirred and contained a manually operated heater. The bath was surrounded by an inch of cork powder. To obtain the most accurate results it was found necessary to adjust the heater to keep the temperature practically constant during each measurement. The thermometer was tapped before each observation. The resistance of the thermistor was measured at roughly equidistant points between 24.5°C and 25.5°C, and the coefficient found by the method of least squares. By taking these precautions it was found that repeat measurements did not differ by more than 0.2%.

The thermometer has been calibrated at the NPL over the same range and with the same degree of partial immersion. The error in the reading varies roughly linearly in this range, so that an observed change of temperature of 1.00°C is really a change of 1.007°C. Observed temperature coefficients have been reduced by 0.7%.

The use of the thermometer at partial immersion is barely significant in this case. The correction for the
emergent column is given by

\[ n \cos n (\theta_1 - \theta_2) \]

where \( n \) is the length of the emergent column in thermometer scale degrees, and \( \theta_1, \theta_2 \) are the temperatures of the bulb and emergent column. In practice \( n \) was about 7 and \( (\theta_1 - \theta_2) \) about 4. The difference in errors at 24°C and 25°C is \( 2 \times 10^{-3} \)°C.

Fig. 11 shows the result of one set of measurements. The actual resistance of the thermistor is \((10^5 - r)\) ohms.

During calorimetric experiments the bridge was connected differently, the resistance box \( r \) being in an arm containing a fixed 100 K resistor instead of in the same arm as the thermistor (see Fig. 3). Under these conditions, at balance

\[
\frac{(r + 100)/100}{T_2/T_1} = T_2/T_1
\]

where \( T_1, T_2 \) are the resistances of the thermists and \( r \) is in KΩ.

Hence \( r = 100T_2 / T_1 - 100 \)

and \( (dr/d\theta)_2 = \frac{100T_2}{T_1^2} \frac{dT_1}{d\theta} - - - - - (0) \)

and \( (dr/d\theta)_1 = \frac{100}{T_1} \frac{dT_1}{d\theta} - - - - - (0) \)
Temperature Coefficient of Thermistor.
The values of $T_1$ and $T_2$ were measured accurately at the operating temperature of the calorimeter (25.05°C), and the effective temperature coefficients of $r$ calculated.

The measurements in carbon (also those of heats of reaction) were not made at a fixed temperature. In general the temperature during irradiation was not exactly the same as during electrical calibration, so that it is necessary to know the variation of $(d r/d θ)$ with temperature.

From equation (7),

$$\frac{1}{T} \frac{dT}{dθ} = -\frac{b}{T^2}$$

Also, for a well matched pair of thermistors, it was found that $T_2/T_1$ was almost independent of temperature. Equations 8 and 9 can be rewritten

$$(dr/dθ)_2 = 100 \frac{T_2}{T_1} \frac{1}{T_1} \frac{dT_1}{dθ}$$

$$(dr/dθ)_1 = 100 \frac{T_2}{T_1} \frac{1}{T_1} \frac{dT_2}{dθ}$$

Using equation (10) it is evident that

$$\frac{(dr/dθ)_{0}}{β_1} = β_2^2$$

$$\frac{(dr/dθ)_{0}}{β_2} = β_1^2$$

which shows that the rate of variation of $r$ with temperature is inversely proportional to the square of the absolute temperature.
The coefficients of different thermistors varied a little, and pairs were chosen that were matched for resistance, temperature coefficient and power sensitivity, in order to mitigate as far as possible the effects of changes in the temperature of the calorimeter box and of changes in the bridge excitation voltage.

3.2.2. Power Sensitivity.

The A.C. power dissipated in the thermistor raises its temperature a little and so reduces its resistance, a typical figure for this power sensitivity of thermistors being 0.4 °C per milliwatt. Many of the measurements have been made using 1.3 volts RMS applied to the bridge, which dissipates 6 mW in each thermistor. This causes a rise of temperature of $2.4 \times 10^{-5}$ °C. As this is similar to the temperature change being measured, it is evident that either the AC power must be extremely stable, or the effects of fluctuations must be eliminated by using a pair of thermistors having equal power sensitivities. Fig. 12 shows what can be done in this way. Here the change in the balance point of the bridge is plotted against the exciting voltage. It is clear that with a well matched pair considerably larger voltages can be used. As an additional precaution a valve voltmeter was built so that the voltage could be kept steady by hand, but in practice this has not proved necessary.
Thermistor Power Sensitivity

- No. 8 alone.
- Pair 19 and 20.
The power sensitivity of the thermistors has another consequence. The instantaneous power, and so the instantaneous resistance, varies during the cycle, and as a result the output voltage from the bridge is distorted. With large exciting voltages a signal at 3 times the input frequency was observed, which made it impossible to find the true balance point.

Generation of third harmonic can be predicted by the following analysis.

Let \( p \) be the instantaneous power in the thermistor
\[ \begin{align*}
\theta & = \text{the temperature rise in the absence of cooling} \\
(\text{C/sec/Watt}) \\
k & = \text{the cooling coefficient} \ (\text{C/sec/C temperature difference}) \\
b_s & = \text{the instantaneous temperature difference from the mean.}
\end{align*} \]

The mean temperature rise is related to the mean power by

\[ 0 = k \bar{\theta} - \frac{A}{p} \]

An oscillating temperature \( \theta \) is superimposed on this.

At any instant
\[ \frac{d\theta}{dt} = \frac{e\theta - k(\bar{\theta} + \theta)}{\bar{\theta}} \]

If \( \bar{\theta} \gg \theta \),
\[ \frac{d\theta}{dt} = \frac{e\theta - k\bar{\theta} = \alpha(p - \bar{p}) \text{ from (12)}}{\bar{\theta}} \]
Let the applied voltage be

\[ v = v_0 \cos \omega t \]

then \[ p = \frac{v_0^2}{2} \cos^2 \omega t \] and \[ \tilde{p} = \frac{v_0^2}{2R} \]

hence \( \frac{d\theta}{dt} = \frac{Gv_o^2}{2R} \cos 2\omega t \).

or \[ \theta = \frac{Gv_o^2}{4R \omega} \sin 2\omega t \quad \cdots \quad (13) \]

The output voltage of a bridge of 4 equal resistors, of which one has a temperature coefficient \( \alpha \), and to which \( 2v_o \cos \omega t \) is applied, can be shown to be

\[ v^1 = v_o \cos \omega t \cdot \frac{\Delta \theta}{2 - \Delta \theta} \]

when \( (\Delta \theta) \) is small this reduces to

\[ v^1 = \frac{\Delta \theta}{2} v_o \cos \omega t \]

Substituting from (13) leads to

\[ v^1 = \frac{\Delta \theta}{2} \frac{Gv_o^3}{12\omega} (\sin \omega t + \sin 3\omega t) \quad \cdots \quad (14) \]

Thus the presence of the thermistor leads to an output signal at balance containing two components, one at the fundamental frequency but 90 degrees out of phase, and one at 3 times the frequency. The first term would also be produced if the thermistor had some inductance, and can be eliminated by a small condenser placed across one arm of the bridge, as shown in Fig. 3. The harmonic term is attenuated by the filter unit, and any remaining signal is eliminated by the synchronous rectifier owing to the phase change.
Similar distorted signals were observed when a carbon resistor was placed in the bridge. In this case the effect is due to the voltage coefficient of the resistor, and no such effect occurs with wire wound resistors.

In fact distortion of the signal is not the limiting factor when higher voltages are applied to the bridge. One limitation is variations in the balance point due to variations in the applied voltage. Another arises from changes in temperature produced by the power dissipated in the thermistor; for example in water above a certain power level fluctuations were observed which I interpret as being the result of convection cells breaking away from the tip of the thermistor.

3.3. Sensitivity of the Apparatus.

Fig. 13 shows the sensitivity obtainable. The bridge contained two thermistors of type F placed in separate vessels of water, and two resistors as shown in Fig. 5. The effect of altering the resistance \( r \) by 0.4 ohms is shown. The temperature coefficient of \( r \) is 4.6 K per \(^\circ\)C. The R.M.S. noise on the record is about 0.05 inch, which is equivalent to \( 2 \times 10^{-6} \) or \( 10^{-7} \) volts at the input of the detector. Actually the first valve (type E88CC) produces 4\( \mu \)V of flicker noise referred to the input, but the recording potentiometer is too slow to respond to most of this noise.
A small break in the mean line is also shown shortly after the 0.4 ohm calibration, and in practice this type of irregularity has been the limiting factor rather than the noise level. A bridge containing resistors only produces no more noise than one with thermistors.

The record of Fig. 13 was obtained using 4 volts applied to the bridge. Usually this sensitivity has been more than enough, and 1.5 volts has been the normal voltage used. 4 volts is about the maximum before the occurrence of instability due to convection cells.

This sensitivity is a little but not much greater than other reported figures. For example Goodwin (1959) could "steadily detect 10^-5 °C," using a thermistor and a galvanometer amplifier. The same sensitivity was achieved by Bernier et al (1956) using a thermistor bridge with a D.C. amplifier, and by Charuel and Traynard (1955) using a pair of thermojunctions and a galvanometer amplifier. The sensitivity of the present apparatus could probably be increased by using a higher frequency, where the flicker noise would be less. The low frequency of 20 c/s was chosen to avoid possible difficulties from stray capacities. No serious attempt has been made to increase the sensitivity, as this is adequate for the purpose.
3.4. Carbon Ionization Chamber.

Measured values of energy absorption have been compared with ionization per gm. of air in an ionization chamber. Carbon was used as the sole material in the chamber for several reasons. A pure element is more suitable than a compound since the stopping power can be calculated more accurately. An insulating plastic coated with graphite has the further disadvantage of inhomogeneity. The choice therefore lay between aluminium and carbon but an aluminium chamber shows a larger variation of ionization per unit volume with X-ray energy, and also with the size of the chamber, due to the effects of delta rays as discussed in Section 2.1.2.

The chamber has the form of a flat cylinder, the collecting volume being 3 cm diameter by 5 mm deep, the collecting electrode being a plate 2.6 cm diameter by 1 mm thick lying in the centre. A sectional view is shown in Fig. 14. The chamber is permanently connected to a double-screened cable. An earthed shield is carried forward from the inner screen to within one mm of the collecting volume, so that currents in the insulator across which H.T. is applied are reduced as far as possible, while at the same time all the ionisation in the air-filled cavity can be collected.
Fig. 14. Section of Carbon Ionisation Chamber.

3 6BA Nylon Screws

Copper, Distrene, Graphite, Aluminium

Scale 2/1
The volume of the chamber is measured by weighing the mercury needed to fill the air volume; the plug in the side of the chamber is removed for filling, and on replacing the plug the excess mercury escapes through the central hole.

The cable has to be cut to enable the chamber to be weighed. This was done after the measurements of energy absorption in water. The chamber was filled with mercury three times, and a radiograph taken on each occasion to estimate the quantity of mercury trapped around the plug.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Weight of Mercury</th>
<th>Estimated weight of Mercury round plug</th>
<th>Weight of Mercury in ionization volume</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42.04 gm.</td>
<td>0.39 gm.</td>
<td>41.65 gm.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>41.94</td>
<td>0.22</td>
<td>41.72</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>41.97</td>
<td>0.31</td>
<td>41.66</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>41.68</td>
<td>3.078 cm³</td>
</tr>
</tbody>
</table>

This figure is probably accurate ± 0.2%. By direct measurement of the chamber, the volume was estimated to be 3.062 cm³ ± 0.5%. The chamber was reconnected to the cable before the measurements of energy absorption in carbon, and the volume was later re-estimated in the same way, giving 3.085±0.2%. 
Saturation measurements have been made using pulsed radiation generated at 8 M.V. In common with the observations of Bernier et al (1966) and of Reid and Johns (1961), complete saturation could not be achieved. Reid and Johns interpret this as being due to initial recombination within more densely ionized parts of the electron tracks, a greater field strength being needed to eliminate this than for general recombination. Kara-Mikhailova and Lea (1940) showed that with high field strengths the current is a linear function of the reciprocal of the voltage across the chamber, and that this line can be extrapolated to the axis to give the saturation current. Reid and Johns have done this for two intensities, and found that the recombination loss was independent of intensity. They used continuous radiation for which general recombination would give a straight line when the current is plotted against $1/V^2$ (Boag 1956).

Fig. 15 shows the current plotted against $2/V$ for two intensities of pulsed radiation, at 350 pulses per second. With pulsed radiation general recombination should also give straight lines, and those of Boag's theory are

The ordinate of the graph gives the current as a percentage of the theoretical value at saturation, found by extrapolating the lines to the axis.
Fig 15 Saturation of carbon chamber

Theory

0.009 esu/ft²/pulse
+ 20 rad/s/min

-0.16 esu/ft²/pulse
= 360 rad/s/min
shown together with the measured points. Initial recombination would be independent of dose rate, but there is no sign of this. However, the instantaneous intensity at 360 rads/min is $10^4$ times that of Reid and Johns, and the effect of initial recombination is probably masked by general recombination. The differences between the measured and theoretical curves may be due partly to initial recombination and partly to volumes where the electric field strength is less than its average value. In any case extrapolation to the axis should give the correct result, and corrections on this basis have been applied. There is an indication that ionization by collision is beginning at the highest voltage, and these points have been ignored.

No difference was found between the two polarities, and irradiation of the stem had no effect. The current was measured by a Baldwin-Farmer meter. The voltmeter was calibrated by a potentiometer and the condenser was measured at the NPL, enabling the ionisation current to be obtained in absolute units.

For the calorimetric measurements in water the carbon chamber had to be compared with the chamber of the Baldwin-Farmer instrument. This is discussed in Section 5.2.

The thermal diffusivity of water is so low that (providing convection is avoided) a thermistor will measure the energy absorption "at a point". This is the reverse of the conditions in carbon, where the average energy absorption throughout an insulated piece of carbon is measured. For water the thermal diffusivity is 0.0014 cm$^2$ sec$^{-1}$ deg$^{-1}$, while for carbon it is between 0.4 and 4 depending on the conductivity assumed.

The temperature rise has been measured at the centre of a cylinder 8.5 cm diameter by 9.5 cm high. Some idea of the effect of cooling such a cylinder can be obtained from Carslaw and Jaeger (1947), page 201, where there are graphs of the temperature at the centre of a sphere initially at a uniform temperature and whose surface is suddenly warmed (or cooled) by one degree. A sphere of the same volume has a radius of 5 cm. After 10 minutes the central temperature has fallen by less than 1/100 of a degree. The temperature then falls more rapidly, losing 1/10 of a degree at 30 minutes. In practice the rate of cooling is less since the cylinder loses heat by convection to the surrounding air and the surface is not maintained at the temperature obtaining before an irradiation.
4.1. Arrangement of the Calorimeter.

The cylinders of aqueous media have been irradiated from vertically above. This establishes a stable temperature distribution, inhibiting convection. The medium itself was contained in a thin walled spherical glass bulb. The bulb was attached to the side of a cylinder of perspex, the space between being filled with water. There were no air spaces, either in the bulb or in the cylinder. A thermistor was inserted into the bulb until its tip was near the centre. The exact position of the tip of the thermistor was measured before assembly of the calorimeter and also afterwards from radiographs. The arrangement is shown in fig. 16.

The use of a glass bulb within the perspex cylinder serves two purposes. After an irradiation cooling takes place from the outside surface, and this must set up a convection current. The glass bulb prevents the convection from immediately affecting the medium contained in it. Ultimately convection no doubt occurs within the bulb, but a delay is introduced by dividing the medium into two cells. The other purpose of the glass bulb is to allow very pure solutions to be used. Radiochemical reactions occur in irradiated aqueous solutions, and these may absorb or give out an amount of heat which is an appreciable fraction of the
energy absorbed from the beam. To estimate this correction accurately it is necessary to use a solution whose radiochemistry is well understood. Radiochemical yields are very sensitive to traces of impurities, and are most reliable when glass vessels are used. The radiochemical reactions are discussed further in Section 4.6.

Four of these systems were placed on balsa supports in a square aluminium box with internal dimensions 30 x 30 x 17 cm. The thermistors in diagonally opposite cylinders were connected together to make two pairs, either of which could be selected as shown in Fig. 8.

An aluminium lid incorporating a rubber gasket was then firmly attached and the box immersed in a tank of liquid paraffin whose temperature was thermostatically controlled. Electrical connections to the submerged box were made via Plessey plugs. Liquid paraffin was used to avoid trouble over the electrical insulation.

Fig. 17 is a diagram of the apparatus. The paraffin was made to flow in a definite path. It was forced down by a paddle, passed over a heater and divided to the two sides of the bath, one stream passing over a thermistor. It then
Fig. 17. Mid-plane section of calorimeter in thermostatic bath.
flowed below the calorimeter box before rising at the end and flowing back over the top. The bath was surrounded by 2" of cork powder on all sides except the top where there was \( \frac{1}{2} \)" of celotex. The arrangement was built on a trolley which could be wheeled into the X ray room. The control thermistor was connected in an AC bridge whose output signal was amplified and used to control the current through a pentode with the heater as the anode load. The bath was operated at 25°C. As long as the room temperature was within the range 65-70°C the mean temperature of the bath varied by less than 10⁻²°C, although oscillations of 10⁻²°C occurred with a period of 6 minutes.

All irradiations were made with X rays generated at 8 MeV., using the URC linear accelerator. The trolley was moved so that each cylinder in turn was irradiated. The top of the trolley was brought as near the source of X rays as possible, the focal distance of the thermistors being about 75 cm and the field at this distance 11 x 11 cm. Each cylinder was completely within the X ray beam. The stray radiation at the thermistor in the diagonally opposite cylinder was found to be 0.4% of that in the one being irradiated.
4. Ionization Measurements.

At some point during the measurements the trolley was moved away and the chamber of a Baldwin-Farmer substandard dosemeter was irradiated instead. The geometry was made as far as possible identical to that of the calorimeter. The chamber was inserted through the side of a perspex cylinder having the same dimensions as the others and filled with Lincolnshire Bolus. This is a material having the same X-ray absorption coefficient as water (Lindsay and Stern 1953), a point that was checked for 6 M.V. X rays. Equivalent layers of aluminium, paraffin wax, perspex and celotex were placed above in the appropriate positions.

The Baldwin-Farmer instrument has been calibrated in terms of roentgens using radium by the NPL with X rays generated at 2 M.V. With radium additional caps were used and the ionization extrapolated to zero cap thickness. At 2 M.V. the correction factor supplied by the NPL was divided by 1.02 to allow for the extra cap used, since the NPL figure is intended to give the exposure in free air with an extra cap in position. The two calibrations agreed to 1%. The constancy of the calibration is checked regularly with a strontium beta ray source.
It is necessary to decide if any change in this calibration is needed when the chamber is irradiated with X rays generated at 8 M.V. Assume to begin with that the Tufnol wall of the chamber is still thick enough to provide all the recoil electrons. Let the chamber be irradiated at the two qualities with intensities such that the ionisation is the same. The ratio of the energy absorptions in water is given by

\[ \frac{E_1}{E_2} = \frac{S_1}{S_2} \cdot \frac{a/\mu_1 H_2O / a/\mu_{Tufnol}}{a/\mu_2 H_2O / a/\mu_{Tufnol}} \]

where the subscript 1 refers to the quality of the radiation used in the roentgen calibration (~900 KeV) and 2 to the 8 M.V. X rays (2.6 Mev effective). \( S \) is the stopping power of tufnol relative to air and \( a/\mu \) the real absorption coefficient. If 1.0 roentgen is used at quality 1, \( E_1 = 87.7 \times 1.11 = 97.4 \) ergs/gm (taking \( W = 34.0 \)).

Assuming Tufnol to consist of phenol formaldehyde, the absorption coefficient term is practically unity. The relative mass stopping power term can be estimated from NBS handbook 62, Table 4 for carbon and water, taking \( T_0 = \beta W_0 / \beta \), and is 1.016 and 1.018 respectively. Tufnol must lie between these. The energy absorption \( E_2 \) is then 95.7 ergs/gm of water.

The influence of the phantom material surrounding the chamber must now be considered. Owing mainly to varying
proportions of hydrogen, different phantom materials influence slightly the ionization current, a subject which I discussed in a letter to Physics in Medicine and Biology (Bewley 1960) which is included at the end of this thesis. The letter gives calculations and measurements of ionization in cavities in four commonly used phantom materials. In Lincolnshire Bolus the calculated ionization (relative to Mix D) is 1.037. In phenol formaldehyde the equivalent figure is 1.030. Thus the Lincolnshire Bolus would be expected to increase the ionization very slightly above that occurring in a chamber having thick tufnol walls. Allowing for the contribution from the actual wall of the chamber, the expected increase is about 0.5%.

Combining these corrections, an X ray exposure giving a reading of one roentgen on the Baldwin-Farmer immersed in Lincolnshire bolus should produce an absorbed dose of 95.2 ergs per gm of water at the same position. This factor has been used in Tables 5 and 6 where calorimetric estimates are compared with estimates of absorbed dose by the ionization method.

The use of this factor assumes no loss of ionization by recombination. Saturation measurements at 100 rads per minutes, plotted in the manner of fig 15, show that recombination loss is
less than 0.5% with the normal voltage used (180v.). No correction has been applied for it.

4.3 Observed Temperature Changes.

Figs. 18 and 19 show temperature changes measured by each of the 4 thermistors used in these experiments. In each case the bridge was rebalanced during the irradiation so that the trace after the irradiation is at about the same point on the chart as it was before. Using this method the sensitivity of the chart does not need to be known very accurately, but the rebalancing makes the trace rather more difficult to understand at a glance. For this reason an idealized trace is also shown in fig 20. The quantity obtained from the chart for each irradiation is the change in the resistance $r$ needed to bring the bridge back to the same degree of imbalance.

Fig 20
Idealized temperature record

---

a)  
---

b)  
---

A   C   D   E   F

---
The radiation is on between A and B. With each thermistor except number 6 there is an immediate drop in temperature BC on switching off. This must be due to heating of the thermistor element itself during irradiation. There is then a period of much slower cooling CD lasting for 2 or 3 minutes, which is probably due to loss of heat from the glass stem. Glass has a specific heat of about 0.2 and is warmed to 5 times the temperature rise of the surrounding water. The temperature is then often steady for a few minutes DE (or is changing at the same rate as before the irradiation), and following this there is usually a period of warming EF before cooling begins. This final period of warming is probably due to heat escaping from the glass bulb, or to thermal conductivity within the water since the curve of temperature against depth must be convex leading to the central temperature being a little less than the mean temperature of points at equal distances above and below.

Interpretation is complicated by the fact that the temperature record before irradiation is often slightly curved. One approach (called a) is to draw a line through the part of the record after irradiation which is parallel to the record before. This would accord with the theory of zero heat loss, but is rather artificial when the line is a tangent to a continuously curving trace. Another
method b) is to find the straightest part of the record and extrapolate back to the mid-time of the irradiation. This would be correct if cooling (or heating) were proportional to the temperature change induced by irradiation and occurred immediately, which is certainly not the case. On the other hand when the record before the irradiation is curved, method a) may be difficult to use, method a) is probably the more accurate. The inclusion of method b) gives an idea of the uncertainty involved in the extrapolations. Generally the results of the two methods differ by amounts varying from 0 to 3%. In both cases the temperature during the first few minutes after switching off is ignored, and it is assumed that the radiation has no direct effect on the thermistor other than by heating. These points are discussed below.

4.5.1. Effect of Heating the Glass Stem.

This was investigated in two ways. In the first method a heating coil was wrapped on the glass stem, from the tip to 2/3 of the way back, and the thermistor was inserted into a vessel of water as during irradiation. The temperature of the
thrmistor element rose while current was passed through the coil. On switching off the temperature began to fall, and after a few minutes it returned close to its original value, the difference being about 1% of the temperature rise of water when irradiated by X rays giving the same energy absorption in the glass stem as given by the electric heater. The temperature change fell to within 1% of this final value (on the same scale) 2 minutes after switching off. This was found with thermistor No. 15. The experiment was repeated with a different thermistor, together with an additional pair of thermistors in the vessel to indicate the temperature gradient. On the occasions when the temperature gradient was small the final effect of heating the coil was 0.3%, and the temperature reached 1% of this value 5 minutes after switching off.

In the second method a pair of thermistors was immersed in a thin jelly at a certain temperature $\theta_1$. One was removed and placed in water at $\theta_2$ for a few minutes and then quickly
replaced in the jelly. After a further minute the
temperature trace usually became steady, showing a difference
in temperature from \( \theta_1 \) of less than \( 10^{-3} (\theta_2 - \theta_1) \).
Allowing for the specific heat of glass, this means that the
additional heating of the stem might introduce a positive
error of up to 0.5\(^\circ\)C.

Both these methods suggest that heating of the stem by
X rays may produce a positive error of less than 1\(^\circ\)C, and that
the record for the first few minutes after switching off
should be ignored.

4.3.2. Direct Effect of Radiation on Thermistors.

For this test a pair of thermistors was inserted into
two holes 6 cm apart in a large steel block, with a little
water for thermal contact. Pairs (5,15) and (19, 20) were
used. One thermistor was irradiated with X rays, the other
member of the pair being out of the beam. After several
minutes the resistance settled down nearly to its original
value, the change being between -0.5\% and +1\% of the resistance
change of a thermistor in water irradiated by the same quantity
of X rays. The mean lay between zero and +0.5\%, so that if
the radiation has any direct effect other than heating, it is
equivalent to a heating effect of less than 0.5\(^\circ\)C. The
resistance differed from its final value by less than 1% (on the same scale) at 2 to 4 minutes after switching off. This experiment therefore also shows that the temperature record during the first few minutes after switching off should be ignored.

4.4. Results.

The results of the 3 last series of experiments are shown in Table 5. The only corrections applied here are for geometry (focal distance and absorption corrections) and pressure and temperature. The geometrical corrections are based on the inverse square law and on an absorption coefficient of water of 0.028 cm⁻¹ measured under the same conditions.

On 4.4.59 an additional ring shaped filter was used to give a more uniform distribution of X rays across the cylinders. The flattening filter in use on the 8 MeV machine overcompensates for the piter diagram of X ray production, producing a minimum intensity at the centre of the field (Newbery and Bowley 1955). Measurements across the mid-plane of the cylinders showed the intensity rising to 102% at 2 cm radius. The ring shaped filter compensated for this, but the results on 4.4.59 are not significantly different from the earlier ones, showing that the refinement was hardly needed.
The results with different thermistors cannot be compared at this stage since their temperature coefficients vary. The different media also involve different corrections. There is no clear variation with time of irradiation, although there is some sign of a rising tendency with increasing times using method b). The results with a given thermistor on different days vary about 1%.

The mean results of Table 5 have been converted to absolute terms in Table 6 allowing for the temperature coefficients of the thermistors and by applying a number of corrections as follows.

1. Radiochemistry. One medium was $10^{-3}$ Molar ferrous ammonium sulphate in 0.2 Normal $H_2SO_4$. The radiation induces oxidation of the ferrous ion, liberating further heat, and a correction factor of 0.871 has been applied. The other medium was $10^{-2}$ to $10^{-4}$ Molar $HCOOH$ in $10^{-3}$ Normal $H_2SO_4$, for which there is a factor of 0.969.

These will be discussed further in Section 4.5.

2. The specific heat of the 0.2 Normal $H_2SO_4$ is 0.993 cal/gm. The electronic density (electrons/gm) is not different from that of water.

3. Stray radiation in the other bulb. Corrections varying between 1.003 and 1.007 have been applied for this.
Table 5.

<table>
<thead>
<tr>
<th>Thermistor Number</th>
<th>Date</th>
<th>Medium Time</th>
<th>Ohms per div.</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10.1.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.4.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 FeSO₄</td>
<td>2</td>
<td>125.6</td>
<td>FeSO₄ 4</td>
<td>a) b)</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>125.5</td>
<td>121.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-</td>
<td>123.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>-</td>
<td>124.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>125.3</td>
<td>124.0</td>
<td></td>
</tr>
<tr>
<td>15 FeSO₄</td>
<td>2.1</td>
<td>124.1</td>
<td>HCOOH 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>125.6</td>
<td>121.8</td>
<td></td>
</tr>
<tr>
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<td>124.9</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>-</td>
<td>126.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>124.2</td>
<td>124.7</td>
<td></td>
</tr>
<tr>
<td>19 FeSO₄</td>
<td>2.1</td>
<td>126.6</td>
<td>HCOOH 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.5</td>
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</tr>
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<td></td>
<td>10</td>
<td>-</td>
<td>124.7</td>
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<td>Mean</td>
<td>126.9</td>
<td>123.1</td>
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<tr>
<td>20 FeSO₄</td>
<td>2</td>
<td>124.9</td>
<td>FeSO₄ 3</td>
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</tr>
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<tr>
<td></td>
<td>Mean</td>
<td>124.9</td>
<td>123.6</td>
<td></td>
</tr>
</tbody>
</table>

Notes. Columns headed a) and b) use different methods of interpreting the temperature records -

a) uses the portion of the trace after irradiation which is parallel to that before (where possible).

b) uses the best straight line after irradiation, extrapolated back to the mid-time of the irradiation.
Table 6
Mean Values of Ergs per gm. of Water per "rad" by Ionization Method, using Baldwin-Farmer chamber.

<table>
<thead>
<tr>
<th>Date</th>
<th>10.1.59</th>
<th>1.2.59</th>
<th>4.4.59</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermistor Number</td>
<td>a)</td>
<td>b)</td>
<td>a)</td>
</tr>
<tr>
<td>6</td>
<td>96.0</td>
<td>97.0</td>
<td>98.3</td>
</tr>
<tr>
<td>15</td>
<td>95.4</td>
<td>95.4</td>
<td>99.6</td>
</tr>
<tr>
<td>19</td>
<td>96.1</td>
<td>95.2</td>
<td>97.9</td>
</tr>
<tr>
<td>20</td>
<td>94.5</td>
<td>93.6</td>
<td>94.9</td>
</tr>
</tbody>
</table>

Table 7
Mean Values Weighted by the Number of Observations.

<table>
<thead>
<tr>
<th>Method</th>
<th>FeSO₄</th>
<th>HCOOH</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>95.9</td>
<td>95.1</td>
</tr>
<tr>
<td>b)</td>
<td>95.6</td>
<td>96.8</td>
</tr>
</tbody>
</table>
The temperature coefficients were estimated as explained in Section 3.2.1. The effect of allowing for this is to make the agreement between different thermistors worse. As the derivation of the temperature coefficients is rather indirect they were remeasured with the circuit values actually used during calorimetry, but this confirmed the previous estimates.

4. 5. Radiochemical Corrections.

The corrections applied for radiochemical reactions are rather large. If pure de-aerated water is irradiated with hard X rays, back reactions cause the net decomposition to be virtually zero, and in such a case the radiochemical correction would be negligible. However, this state of affairs is notoriously difficult to achieve and is only possible when using water of extreme purity. The use of a solution whose radiochemistry is well understood is a more practical approach, particularly when the radiochemical products can be measured after the irradiations.

The solutions of ferrous ammonium sulphate and formic acid were made for me by Dr. Ebert, to whom I am most grateful. He used water redistilled from alkaline and acid permanganate. He also carefully cleaned the glass bulbs and thermistors.
and after each experiment he measured the concentrations of ferric ion and hydrogen peroxide produced in the solutions of ferrous ion and formic acid respectively. Taking the dose at the centre of the bulb as representing the average dose received by the solution, the concentration of ferric ion was within 5% of the expected value in each case except number 19 on 10.1.59, when there was a 12% excess of ferric ion. It happens that this occasion also produced the largest difference between methods a) and b). The concentration of \( \text{H}_2\text{O}_2 \) in the formic acid solutions was never more than 8% different from the expected value.

The heats of formation of the various molecules have been taken from N.B.S. Circular 500 (Rossini et al. 1952). A difficulty occurs over ferric sulphate, as significantly different figures are given for the un-ionized salt in dilute solution and for the ions. Also, ammonium complex might affect the heats of formation of the ferrous and ferric salts. For these reasons the heat of oxidation of ferrous ammonium sulphate by hydrogen peroxide was measured at the proper dilution. The result confirms the figures for the ions. I have already described these measurements in a paper (Bewley, 1960) which is included at the end of this thesis.
Previous measurements of the heat of this reaction have been made only with much more concentrated solutions; the thermochemistry of dilute solutions is a useful application of a sensitive microcalorimeter such as the one I have devised.

The calculation of the heat balance of the radiolysis of ferrous ammonium sulphate is based on the products being ferric ion, hydrogen gas (dissolved) and water only. Taking the yield of ferric as $\alpha(\text{Fe}^{3+}) + 15.8$, the reaction per 100 $e^- \cdot v$ absorbed can be written

$$15.6 \text{Fe}^{2+} + 15.6\text{H}^+ + (3.9 - \lambda/2)\text{O}_2 \rightarrow 15.6\text{Fe}^{3+} + \lambda\text{H}_2$$

$$+ (7.8 - \lambda)\text{H}_2\text{O}$$

The yield of hydrogen relative to that of ferric ion has been found by Back and Miller (1957) and by Allen et al (1957) to be $0.0258$ and by Dainton and Sutton (1953) to be $0.0298$. These figures lead to heats of reaction of 14.8 and 14.7 $e^- \cdot v$ per 100 $e^- \cdot v$ absorbed. I was unable to find the heat of solution of hydrogen, but the yield is so small that the error involved must be negligible. The presence of the ammonium complex has been ignored. However, 95% of the heat is produced by a secondary reaction between ferrous ions and $\text{H}_2\text{O}_2$ formed initially (this can be derived from the paper of Dainton and Sutton), and the measured heat of this reaction,
with ammonium present, agreed closely with the calculated value for Fe\(^{2+}\) in solution. The measured temperature rise must therefore be multiplied by 1/114.8 or 0.871.

The radiolysis of solutions of formic acid has been studied by Hart (1954). He measured the yields of H\(_2\), CO\(_2\) and H\(_2\)O\(_2\) and the consumption of O\(_2\), and found them nearly independent of the concentrations of HCOOH and O\(_2\) over a wide range. Assuming that no other products are formed, the extra heat liberated per 100 e-v absorbed in solutions of 10\(^{-2}\), 10\(^{-3}\) and 10\(^{-4}\) Molar HCOOH is 3.7, 2.8 and 2.8 e-v respectively. These figures are probably not significantly different. Taking a mean of 3.1 e-v, the correction needed is 1/1.031 or 0.969. The post radiation reaction between H\(_2\)O\(_2\) and HCOOH is much too slow to be of importance, as can be seen from the fact that H\(_2\)O\(_2\) in the proper concentration was measured on the day after the irradiations.

The relative amounts of energy liberated per gm. of the two solutions should be 0.969/0.871 or 1.112. This can be compared with measured values using Table 5, after removing the factors already applied for
radiochemistry. Thermistors 15 and 19 were used with both solutions, and they give the results shown in Table 8. The measured ratio is 2.6% less than the theoretical value.

Table 8.

Energy Liberation in Ferrous Sulphate Divided by Energy Liberation in Formic Acid

<table>
<thead>
<tr>
<th>Thermistor</th>
<th>a)</th>
<th>b)</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1.074</td>
<td>1.093</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.092</td>
<td>1.074</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1.083</td>
<td>1.083</td>
<td>1.112</td>
</tr>
</tbody>
</table>

4.6 Cerenkov Radiation and Fluorescence.

No allowance has been made for loss of energy by Cerenkov radiation. In the energy band in which the aqueous medium is transparent, the Cerenkov radiation escapes from the system and should be allowed for, but it turns out that the loss of energy is too small to be significant.
The number of light quanta with frequency $\nu$ emitted per cm of beta ray path is given by (Staub 1953)

$$N(\nu)d\nu = \frac{4\pi^2 e^2}{hc^2} \left( 1 - \frac{1}{\mu^2 \beta^2} \right) d\nu$$

where $\mu$ is the refractive index of the medium. The energy radiated is then

$$E(\nu)d\nu = \frac{4\pi^2 e^2}{c^2} \left( 1 - \frac{1}{\mu^2 \beta^2} \right) \nu d\nu$$

An upper limit to the energy radiated can be found by assuming the medium to be transparent for $\lambda > 2200$ A.U., $\mu=1.35, \beta=1$. Integrating,

$$\int_0^{\nu_0} E(\nu)d\nu = \frac{4\pi^2 e^2}{c^2} \left( 1 - \frac{1}{\mu^2 \beta^2} \right) \frac{\nu_0^2}{2} = \frac{2\pi^2 e^2}{\lambda^2} \left( 1 - \frac{1}{\mu^2 \beta^2} \right)$$

This comes to 2600 e-\nu/cm, which is to be compared with an ionization loss of about 2 MeV/cm for energetic $\beta$ rays. Cerenkov loss is thus less than 0.1% of the total energy loss, and can be neglected.

The emission of light from water bombarded by energetic $\beta$ rays has been investigated by Belcher (1953). He dissolved various radioactive isotopes in water and measured the light with a photomultiplier. The rays from $^{35}$S are not sufficiently energetic to excite
Cerenkov radiation, and in this way fluorescence alone could be measured. In every case Belcher found that fluorescent radiation was very weak, and he estimated that with more energetic $\beta$ rays less than $2\%$ of the light produced was due to fluorescence. He also confirmed the theoretical intensity of the Cerenkov radiation. Ferrous sulphate and formic acid solutions are unlikely to be much more strongly fluorescent than the solutions studied by Belcher, since the only fluorescent inorganic solutions are those containing complexes of Tl, Pb, Sn, UO$_2$, and Pt, while with organic materials a carbon - carbon double bond is required (Schan 1943).

4.7. Discussion of Results.

Returning to Table 6, it will be seen that the measured absorption of energy in water is between $0$ and $7\%$ less than expected from the ionization measurements. If only method a) is used the discrepancy lies between $0$ and $5\frac{1}{2}\%$. This is larger than uncertainties in the ionization method would lead one to expect. The discrepancy cannot be due to irradiation of the glass stem since the error due to this (if any) lies in the direction of too large a rise of temperature.
A disturbing feature of the results is the variation between thermistors. Number 6 gives a temperature rise 3% greater than is given by number 20, using the same medium. This suggests an undetected error which may be causing the generally low results. Another possibility is an error in the corrections for radiochemical reactions. Table 6 shows that the relative temperature rise in the two media is 2.6% different from the theoretical value. This is not due to the differences between thermistors since the comparison was made separately for numbers 15 and 17. It is also not due to a general difference between the measurements on different days since the results with numbers 6 and 20 (using $\text{FeSO}_4$ on each occasion) show no significant variation. The observed difference of 2.6% is perhaps not quite beyond the experimental error, but it suggests that at least one of the corrections for radiochemistry may be slightly in error.

Yet another possibility is that energy is carried out of the solution and deposited on the wall by sub-excitation electrons. These have been proposed by Klitzmann (1955). The lowest excitation
energy of water is 6.7 e-v. Once recoil electrons have lost sufficient energy to fall below this level Platzmann considers that further loss of energy takes place very slowly and that the electrons may travel quite large distances before being captured. He also considers that about 20% of the energy absorbed passes through this form. However, it is doubtful whether energy could be carried several cm in this way, particularly in the presence of a considerable concentration of sulphuric acid.

In view of these uncertainties and of the low result of the calorimetric measurements in water, I decided to obtain checks on the absorbed dose by measurements with the Fricke Dosimeter and the carbon chamber of known volume. These are discussed in the next sections. They show that the calorimetric measurements are indeed too low, and as a result I made a further series of calorimetric measurements of the absorbed dose in carbon, described in Section 6.
5. OTHER ESTIMATES OF THE ABSORBED DOSE IN WATER.

5.1. Fricke Dosimeter.

The Fricke dosimeter has also been used to obtain a check on the absorbed dose. The opportunity was taken to measure the dose from the electron beam at the same time, in order to have a direct measurement of the polarization correction.

The solution \(10^{-3}\) Molar Fe\(^{2+}\) in 0.8 Normal H\(_2\)SO\(_4\) was irradiated in perspex cells measuring 2 x 4 x 0.45 cm. Two cells standing side by side were irradiated each time, one of the cells containing \(10^{-3}\) Molar Na Cl in addition to the ferrous solution. The addition of Chloride ion enables the presence of impurities to be detected (Dewhurst 1952). In the absence of impurities the two solutions give the same yield of ferric ion, but when impurities are present the yields are usually markedly different. The cells were surrounded on all sides by perspex, the thickness in front being that required to bring the centre of the cell to the peak of the depth dose curve measured with a disc-shaped ionization chamber having a gap of 1mm. The yield of ferric ion was compared with the ionization in a Baldwin-Farmer chamber, placed at the depth in perspex giving maximum ionization.
Depth dose curves in perspex are shown in Fig. 21. These were made with the disc-shaped ionization chamber at a fixed distance, the thickness of perspex in front of the chamber being varied. With X rays the chamber was at 102 cm focal distance, and with electrons it was at 125 cm from the gold scattering foil, at the end of the treatment cylinder, as described by Batchelor et al (1959). When measured with the Baldwin-Farmer chamber the peak was found to be 2 mm further back (measured to the centre of the chamber), no doubt due to the larger air volume. Accordingly 2 mm of additional perspex was used with this chamber, the centre of the chamber being placed at the same focal distance as the centre of the ferrous solution.

Irradiations of solutions and chamber were made successively, using another chamber as monitor. The same dose rate of 100 rads/min was used with the X ray and electron beams.

In evaluating the results the extinction coefficient was taken as 2124 at 20°C (Henderson and Miller (1960). Measured values of the extinction
Fig. 21  Depth dose curves at constant focal distance

Electrons

-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100

Depth in cm. perspex

FeSO₄ Soln.

Chamber

X-rays

-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100

FeSO₄ Soln.

Chamber

Depth in cm. perspex
coefficient using standard solutions of ferric ion were in agreement with this figure. The optical density increases with temperature at 0.7% per °C (Haybittle, Saunders and Swallow 1956). The density of 0.8 N. Sulphuric acid is 1.025, for which a correction has been applied. The ionization in the chamber has been converted to absorbed dose in water by the method explained in Section 4.2, except that the use of perspex instead of Lincolnshire bolus alters the figure to 95.6 ergs/gm of water per "roentgen". The same figure has been used for the electron beam, in order to demonstrate the effect of the polarization correction.

Experiments were made on two days. On each occasion two irradiations of the solution were made with the X ray beam and two with the electron beam, together with irradiations of the chamber. The addition of Chloride ion altered the density by amounts varying from -1% to +3%. As there seemed to be little sign of impurity by this test, only the results with no Chloride present have been used. The results are shown in Table 9.
Table 9

Absorbed Dose in Water by Fricke Dosimeter and Ion Chamber

<table>
<thead>
<tr>
<th>Date</th>
<th>Radiation</th>
<th>O.D. at $20^\circ$C</th>
<th>Absorbed dose in water by $\text{Fe}^{2+}$</th>
<th>Ion Chamber</th>
<th>$\text{Fe}^{3+}$ dose</th>
<th>Ion chamber dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.7.60</td>
<td>$X$</td>
<td>.1121</td>
<td>3181 rads</td>
<td>3165 rads</td>
<td>1.005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta$</td>
<td>.0993</td>
<td>2818</td>
<td>3186</td>
<td>0.884</td>
<td></td>
</tr>
<tr>
<td>7.9.60</td>
<td></td>
<td>.1098</td>
<td>3116</td>
<td>3089</td>
<td>1.009</td>
<td>0.994</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.1086</td>
<td>3082</td>
<td>3094</td>
<td></td>
<td>0.998</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>.1089</td>
<td>3065</td>
<td>3420</td>
<td>0.896</td>
<td>0.890</td>
</tr>
</tbody>
</table>

For the X ray beam the Fricke Dosimeter is in excellent agreement with the ionization chamber taking $W = 34.0$. The standard error of this measurement is estimated to be made up of

- Extinction Coefficient and dimensions of cell $1.0\%$
- $G(\text{Fe}^{3+})$ $1.2\%$
- Experimental observations $0.5\%$
- Non-uniformity of dose over cell volume $0.2\%$
- Root square sum $\pm 1.7\%$
Dr Ebert prepared the solutions and made the measurements of optical density.

§1.1. The Polarization Correction for the Electron Beam.

The measurements with the electron beam are less accurate for two reasons. Only one polarity was applied to the ionization chamber, and owing to collection of an electron current the mean of both polarities should be used. Also the chamber is rather too large to receive uniform irradiation. Both these points were allowed for by comparing the Baldwin-Farmer with the disc-shaped ionization chamber already referred to, using the X-ray and electron beams. The mean of both polarities was used with this chamber.

Three comparisons of this kind gave a mean result that the ionization in the Baldwin-Farmer chamber irradiated with electrons should be reduced by 2.3%. The ion chamber then overestimates the dose by 8.5%, compared with the Fricke dosimeter.
To compare this with the expected error arising from the polarization correction it is necessary to know the energy of the electrons. At a depth of 1.3 cm of water the energy would be about 5.5 MeV if there were no scattering. With scattering the mean energy must be less, perhaps about 4.5 MeV. At this energy the polarization correction in water is 7.3% (NBS Handbook 62). The agreement is as close as can be expected in view of the uncertainties in both estimates. The experiment confirms that a correction is needed and that the theoretical value is not far wrong.

An attempt has also been made to confirm the polarization correction using photographic films. A 3 line film was wrapped in black paper and exposed in a block of perspex to the X ray and electron beams. Two methods were used; in one a series of films were placed at various depths, each being perpendicular to the direction of the beam, and in the other a single film extended over a range of depths by being angled at 60° to the beam (30° to the surface of the perspex block). Two sets of exposures were made by each method, and they all indicated that the polarization correction was unity± 2%.
The use of films has two disadvantages compared with the Fricke dosimeter. The sensitivity of the former to soft X rays is of the order of 30 times the sensitivity to megavoltage X rays, while the yield of the latter varies by only a few percent over the same range. The lack of an observed polarization correction for the electron beam might therefore be due to a very small contamination of the beam by soft X rays. The other point is that using film the significant factor is probably the polarization correction in silver bromide. This amounts to only about half the correction in water. Considering both these points it seems reasonable to reject the measurements with films. The fact that the stopping powers of silver bromide and water are not quite proportional at different electron energies is a theoretical objection to the use of film for accurate depth dose measurements with electron beams.

I am grateful to Miss J.A. Stevenson for doing the experimental work with the films.
5.2. Carbon Chamber.

The chamber has already been described in Section 3.4. When used to estimate the absorbed dose in water from X rays generated at 8 M.V., the chamber was laid on a block of tissue equivalent material. An additional 2.5 mm of carbon over the chamber was needed to bring the ionization to a maximum. The ionization was compared with that in the Baldwin-Farmer chamber placed at 2 cm deep in mix D wax (Jones and Raine, 1949). In both cases the surface was at 100 cm focal distance. As a result the centre of the carbon chamber was 0.5 cm closer to the target than the centre of the Baldwin-Farmer chamber, for which a correction of 1.0% is applied.

230 volts was applied to the chamber which was irradiated at 100 rads per minute or 0.005 esu per cc per pulse. Reference to fig 15 shows that the current should be within 0.1% of saturation.

The field size was 8 x 8 cm. With materials of different densities the same scattering conditions are obtained if the linear dimensions are in the ratio of the electronic densities. On this basis the field size used with the carbon chamber should have been 5.3 x 5.3 cm, or 28 cm². However, altering the diaphragms alters
the flux of scattered radiation coming from the machine. Instead, the carbon chamber was not surrounded by any scattering medium, and the irradiated area of 6 cm diameter, or 28 cm$^2$, is just correct. This procedure leads to too much back-scattered radiation from the part of the field area overlapping the chamber, but the error involved is negligible as the quantity of back-scattered radiation is extremely small at 8 M.V.

The chambers were compared on 4 occasions, using the transmission chamber in the X ray head as a monitor. The relative ionizations, corrected to $22^\circ$C and 760 mm Hg, were found to be 5.381, 5.397, 5.394 and 5.398, giving a mean of 5.393 ± 0.1%. The absolute ionization was obtained from the measured voltage sensitivity of the electrometer and the value of the condenser in the feedback circuit.

The relative humidity of the air was measured on two of the occasions and found to be 50%. The effect of humidity has been considered by Barnard, Aston and Marsh (1960). From their Table 2 this degree of humidity should reduce the ionization by 0.2%.
The energy absorbed in the wall of the chamber is related to the ionization by equation (1):

\[ E = J W \overline{S_m} \]

For an air-walled chamber for which \( \overline{S_m} = 1.00 \), containing dry air at 22°C and 760 mm and in which the ionization is 1 esu/cm\(^5\), \( E \) is \( 87.7 \times 295/273 \) ergs/gm (assuming \( W = 34.0 \)). The energy absorbed in the wall of the carbon chamber is therefore given by \( E = 94.7 J \overline{S_m} \).

The value of \( \overline{S_m} \) has been found by the method of Section 2.1.2. for the spectrum of X rays generated at 8 M.V. (X ray spectra are discussed further in Section 6.6). The ionization potentials of Table 2 give a figure of 0.983, while those of NBS Handbook 62 give 0.996. Allowing 0.4\% for the Spencer-Attix modification for \( \delta \) rays the figures become 0.987 and 1.000.

The absorbed dose in water is found by multiplying the absorbed dose in carbon by the ratio of the real absorption coefficients, \( \alpha_{H_2O}/\alpha_c \). If only the Compton effect is considered this is equal to the ratio of the number of electrons per gm, which is 1.111. Pair production in oxygen increases this
figure slightly, and the quantity \[ \frac{\int_0^{E_{\text{max}}} E \sigma N_{\text{He}_2} \, dE}{\int_0^{E_{\text{max}}} E \sigma N_{\text{CC}} \, dE} \]
has been evaluated over the X-ray spectrum, giving a figure of 1.116.

The absorbed dose is again estimated from the Baldwin-Farmer chamber by the method of Section 4.2. Mix D gives 1.8% less ionization than Lincolnshire bolus. Also it was found that the chamber was not quite at the peak of the depth dose curve, the true peak being 0.8% greater. The absorbed dose in water is then \( 95.2 \times 1.010 = 96.2 \) ergs/gm per "roentgen" measured in mix D.

When all these factors are used, the absorbed dose in water according to the carbon chamber divided by that according to the Baldwin-Farmer is .997 using stopping powers from NBS 62 and .985 using those derived from Table 2 of this thesis.

The error of these estimates depends mainly on the error in the relative stopping power factor. The standard error of the ratio is made up of
Volume of the chamber 0.2%
Saturation of the chamber 0.1%
Voltage calibration 0.2%
Calibration of capacitor 0.1%
Standard error of observations 0.1%
Factors of distance and obtaining the peak ionization 0.3%
Stopping power (Section 2.1.3.) 1.1%

Root Square Sum 1.4%

The uncertainty in $W$ does not appear here since the ionization in 2 chambers is being compared. The value of $W$ affects equally both estimates of absorbed dose. This comparison is really a check at 8 M.V. of the calibration of the Baldwin-Farmer made previously at 2 M.V. and with radium.

5.3. Derivation of $W$.

Values of $W$ can be derived by combining the results of the calorimetric measurements in water with the measurements using the carbon chamber. The mean results of the calorimetric measurements were given in Table 7 (page 87), assuming $W = 34.0$. The measurements with the carbon chamber indicate that the ionization measurement referred to in Table 7 should be reduced
by factors of .997 or .985 depending on the stopping power figures used. Table 10 is a conversion of Table 7 in terms of \( W \); for example the first figure is found as follows - \( 0.959 \times 34.0/0.997 = 32.7 \) e-v per ion pair.

Table 10.

Values of \( W \) from Measured Energy Absorption in Water and Ionization in a Carbon Chamber, Stopping Powers from NBS 62.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Method a)</th>
<th>Method b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeSO(_4)</td>
<td>32.7</td>
<td>32.4</td>
</tr>
<tr>
<td>HCOOH</td>
<td>33.6</td>
<td>33.0</td>
</tr>
</tbody>
</table>

It should be noted that the results in Table 10 do not depend on the calibration of the Baldwin-Farmer chamber. They are based on a comparison of measured energy absorption in water with ionization in the carbon chamber, the Baldwin-Farmer being used only to link the two. Since the calibration of the Baldwin-Farmer with 8 M.V. X rays is less rigorous than that of the carbon chamber, the data of Table 10 is more fundamental than that of Table 7.
Except for the result with HCOOH using method a) the values of $W$ are all outside the range 33.5 - 34.0 e-$v$/ion pair which was suggested in Section 2.1.1. as the range of uncertainty in $W$. Use of the alternative stopping powers would increase these figures by 1.4%, still leaving them rather low. For this reason, and because of the rather poor internal consistency of the measurements in water, further measurements have been made of the energy absorption in carbon. They are described in Section 6.

6. MEASUREMENTS OF ENERGY ABSORPTION IN CARBON.

It was pointed out in Section 4 that the thermal diffusivity of carbon is about 1,000 times that of water, so that the average absorption of energy in a thermally insulated piece can be measured. Carbon is the most suitable material for this type of measurement since its atomic number is close to that of tissue, and being a pure material no correction is required for radiochemical reactions. The disadvantages of using aluminium for a comparison of energy absorption with ionization were pointed out in Section 3.4.
Measurements have been made with Cobalt $\gamma$ rays and X rays generated at 14 M.V., 8 M.V. and 300 KVP. At the first 3 qualities the energy absorption was compared with ionization in the carbon chamber described in Section 3.4. At 300 KVP the exposure dose was measured in roentgens.

The carbon block in which energy absorption was measured was made to have a geometry very similar to that of the ionization chamber. In addition an electric heater was included in the absorbing element, making it unnecessary to know the temperature coefficient of the thermistor.


The absorber is shown in fig. 22. The element whose temperature is to be measured is a carbon disc 3 cm. diameter by 8 mm. thick. The element is supported on 3 small spigots of perspex which are fixed to an outer block or baffle 6 cm. diameter by 5.8 cm. high. There is a gap 2mm. wide all round the element. The baffle (made in two halves) stands on 3 other perspex spigots which are fixed to the base of the aluminium box which was used to contain the water samples (See Section 2.1.).
Fig. 22 Carbon Calorimeter.

Scale 2/1
As with the measurements of energy absorption in water, a control thermistor is placed in another block of carbon with outside dimensions the same as those of the baffle. The two blocks are 17 cm. apart and are painted with aluminium paint to reduce radiation losses. The aluminium box is evacuated by a two stage rotary pump to a pressure of 0.02 mm. Hg. A general view of the calorimeter is shown in fig. 23.

The aluminium box was surrounded on all sides by 6.3 cm. of celotex. It was found to be unnecessary to use a thermostatic bath provided the room temperature does not vary by more than a few degrees during the day. This represents a very convenient simplification of the apparatus, which is only possible through the use of a control thermistor.

The element contains a thermistor and a heating coil. The thermistors, of type M, were prized off their copper backing and stuck with Araldite onto a flattened portion of a carbon rod, the rod being pushed snugly into a hole in the carbon block. One of the thermistors is labelled T in fig. 22.
Fig 2.3
Heating coils are shown labelled C. There is one in the element and one in each half of the baffle. Each takes the form of a zigzag of 48 SWG enamelled Eureka sandwiched between two carbon discs. The wire was stuck to one disc with perspex cement, the other disc then being stuck on with more perspex cement.

The connecting wires to the thermistors and heaters are 46 SWG copper, except for the heater in the element where 42 SWG was used to reduce the resistance.

The presence of the thermistor and heater means that the element contains other materials besides carbon. Also the carbon itself contains a number of impurities. The proportions by weight of these other materials contained within the element are as follows:-

<table>
<thead>
<tr>
<th>Material</th>
<th>Parts per Million</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermistor embedded in lead glass</td>
<td>700</td>
</tr>
<tr>
<td>Platinum leads to thermistor</td>
<td>300</td>
</tr>
<tr>
<td>Heater (Eureka)</td>
<td>300</td>
</tr>
<tr>
<td>Polythene sleeving</td>
<td>200</td>
</tr>
<tr>
<td>Perspex Cement</td>
<td>8400</td>
</tr>
<tr>
<td>Impurities in carbon</td>
<td></td>
</tr>
<tr>
<td>Boron</td>
<td>300</td>
</tr>
<tr>
<td>Iron</td>
<td>120</td>
</tr>
</tbody>
</table>
The presence of platinum and lead causes the element to absorb slightly more energy from the X ray beam than would be absorbed by pure carbon. However, with the megavoltage radiations the correction is less than 0.1% and can be neglected. In the measurements with 300 KVP radiation these impurities are the largest source of uncertainty.


The absorber has been irradiated from above, with a field large enough to cover the whole of it. Under these conditions heat is liberated throughout the material, and the temperature rise of the central element is about the same as the average temperature rise of the surrounding baffle.

The electric heaters in the baffle were designed to simulate this state of affairs. There is a heater in each half in case of poor heat transfer from one half to the other. Each is about 100 ohms and they are connected in parallel. The heater circuit is shown in fig. 24. The relative amounts of heat liberated in the element and baffle can be altered by changing \((R_1 + R_2)\). The current in the element is measured by
Fig. 24 Heater Circuit

To Potentiometer

R₁  R₂

50 Ω

Central Element

Calorimeter

Baffle

Central Element
a potentiometer placed across a series resistor, and the heat is calculated from the current and the resistance of the heater. The changeover switch arrangement enables the potentiometer to be balanced without heating the calorimeter; if the potentiometer is not correctly set beforehand, current can be fed back from it into the heater circuit.

Electric heating cannot exactly reproduce the conditions occurring during irradiation. The heat produced in the heating coil has to pass into the carbon, and there is a further thermal barrier between the thermistor and the rest of the carbon element. As a result some time is needed before the heat becomes uniformly spread. Fig. 25 shows the temperature record following a pulse of electric heating delivered to the centre alone; the thermistor registers its maximum temperature after an interval of \( \frac{1}{2} \) minute and thereafter shows cooling at 10% per minute. Consequently, in interpreting the records of electric heating runs the first half minute after switching off has been ignored.
The presence of a thermal resistance between the heating coil and the carbon might lead to some loss of heat down the connecting wires. Some idea of the possible significance of this can be found as follows. If all the perspex cement were spread evenly between the two halves of the element, the separation would be 0.1 mm. The worst case occurs if the heater is halfway between them, with heat conduction through perspex. The thermal time constant would be 0.04 sec. During this time some heat would escape down the connecting wires. This can be estimated from the theory of heat conduction in solids (Carslaw and Jaeger p. 41). For a semi-infinite solid whose surface is kept at zero temperature and having an initial temperature of one degree, the temperature after time \( t \) is given by

\[
\text{erf} \left( \frac{x}{2 \sqrt{12} t} \right)
\]

where \( x \) is the distance from the surface and \( \sqrt{12} \) the thermal diffusivity, and \( \text{erf} \ = \frac{2}{\sqrt{\pi}} \int_0^x e^{-z^2} dz \)

The rate of flow of heat per unit area across the boundary can be shown to be \( \frac{dQ}{dt} = \frac{K}{\sqrt{\pi x t}} \)

where \( K \) being the thermal conductivity. This method gives an
upper limit to the loss of heat to the connecting wires, which in 0.04 seconds amounts to 0.2%. Even this is not lost since it mostly flows back to the heater shortly after.

An analogous problem concerns the fate of the heat generated in the connecting wires. There are 2 wires each 12 cm long, of 42 SWG copper, having a resistance of 0.5 ohm. The resistance of the heater is 106.8 ohms, so that an additional 0.5% of heat is generated in the leads. Some of this is lost by conduction to the ends, and some by radiation. For a black body radiation loss would be at 7% per second. Conduction loss is non linear, but in 10 seconds about half the heat would be lost to the two ends. The two modes are of the same order. Since the first half minute after heating is ignored, all the heat in the wire has been dissipated by the time the temperature record is of any value. Assuming the same heat loss to each end, less than half the heat passes into the element and the possible error amounts to 0.2%
The presence of the heating coil requires the element to be in two halves, and as the thermistor is in the upper half the question arises as to whether the two halves are in sufficient thermal contact to be treated as a single block. This was tested by the arrangement shown in fig. 26 a). BC is the central element of the calorimeter. A and D are two other carbon discs with heating coils cemented to them. A weight was placed on top to keep the discs in good contact. The assembly was stood on 3 spigots in the calorimeter box, which was evacuated. Short pulses of heat were supplied alternately to heaters E and G. Poor thermal contact between B and C would lead to the maximum temperature being observed a little later following a pulse of heat in G than following a pulse in E. Fig. 26 b) shows the type of record obtained. JK was 1.7 minutes and JL 2 minutes. The rate of cooling afterwards was 3.7° per minute.

The thermal resistance BC can be worked out approximately from these results using the electrical analogue shown in fig. 26 c). The capacitors $C_1$ and $C_2$
Fig. 26 a)

Fig. 26 b)

Fig. 26 c)
represent \((A + B)\) and \((C + D)\). \(R_3\) is the thermal resistance \(BC\). \(C_4\) represents the thermistor and \(R_4\) is its thermal insulation from \(B\). \(R_1\) provides for heat losses. A charge \(Q\) is suddenly supplied to \(C_1\) or \(C_2\), and the voltage across \(C_4\) is observed.

The analysis of this circuit is very laborious. The problem can be simplified by omitting \(C_4\) \(R_4\); this does not make much difference since the thermistor and its mounting represent only \(0.1\%\) of the total heat capacity. The time delay \(KL\) must now be identified with the time to reach maximum voltage on \(C_2\) after a charge \(Q\) has been supplied to \(C_1\).

Putting \(C_1 = C_2 = 0\) and \(R_1 = R_2 = R\), and letting \(q_1, q_2\) be the charges on the condenser at time \(t\),

\[
\begin{align*}
\frac{dq_1}{dt} &= \frac{V_1 + V_1 - V_2}{R + R_3} \\
\frac{dq_2}{dt} &= \frac{V_2 - V_1 - V_2}{R + R_3}
\end{align*}
\]

These can be combined to give

\[
CR_3 \frac{d^2V}{dt^2} + 2(1 + R_2/R)\frac{dV}{dt} + \frac{2 + R_3/R}{CR}V = 0
\]

The general solution to equations of this type is

\[
V = Ae^{-\lambda_1 t} + Be^{-\lambda_2 t}.
\]
If a charge $q$ was placed on $C_1$ at $t = 0$, then at $t = 0$ $V_2 = 0$ and $A = 2B$.

Hence

$$\frac{dV_2}{dt} = \lambda_1 \Delta e^{-\lambda_1 t} + \lambda_2 \Delta e^{-\lambda_2 t}$$

The maximum voltage is reached when $dV_2/dt = 0$, when

$$t = \frac{1}{\lambda_2 - \lambda_1} \log \frac{\lambda_2}{\lambda_1}$$

By using other initial conditions it can be shown that

$$\lambda_1 = 1/CR$$

and $\lambda_2 - \lambda_1 = 2/CR_3$

Putting $t = 0.3$ minutes and $1/CR = 0.037 \text{ min}^{-1}$, it can be shown that $CR_3 = 0.1$ min. The disc $A$ (fig. 26 a) has 6 times the mass of $B$, so that in the absence of $A$ and $D$ the time constant for heat to pass from one half of the element to the other is 1/70 min.

This analysis shows that the two halves of the element are in excellent thermal contact. If the transmission of heat were entirely through the heater, the thermal time constant from heater to carbon would be of the order of $10^{-5}$ sec. This of course represents a lower limit, which does not conflict with the upper limit of 0.04 sec. given earlier.
It has already been mentioned that the central element loses heat to the baffle at the rate of 10% per minute. Electric calibrations can be arranged to heat both to exactly the same degree, but in general this will not be true during irradiation. It is important to find the effect of this rather rapid rate of cooling on the interpretation of the temperature records. This can be done by an analysis of the electrical analogue shown in fig. 27.

\[ C_1 = 1 \quad \frac{R_1}{10} \]
\[ C_2 = 27 \quad \frac{R_2}{3.6} \]

CR in Minutes.

\[ C_1 \] represents the central element and \( C_2 \) the baffle. The baffle cools to its surroundings about 10 times more slowly than the element to the baffle.

The analysis is of the same kind as that of the circuit of fig. 26 b), and gives
\[ V_1 = Ae^{-\lambda_1 t} + Be^{-\lambda_2 t} \]  

where \( \lambda_1 = 0.103 \) and \( \lambda_2 = 0.01 \). The constants A and B depend on the initial conditions. Three of these have been used - at zero time \( C_1 \) is charged to unit voltage and \( C_2 \) to a voltage \( \lambda \), where \( \lambda = 0.9, 1.0 \) and 1.1. The form of equation 15 for each of these conditions is shown in fig. 28. The longest period of heating used regularly has been 3 minutes, and the cooling curves for this condition have also been calculated. When plotted with zero time at the centre of the heating period the curves are indistinguishable from those of fig. 28, except that when \( \lambda = 1.1 \) the voltage on \( C_1 \) is 0.05% less than in the case of instantaneous charging.

The procedure used to allow for cooling has been to extrapolate the record before and after heating to the centre of the heating period. In the case of electric calibrations the first half minute after the heating has been ignored. Linear extrapolation has often not been possible; the record tends to be continuously curving as a result of previous heating.
runs, and many of the extrapolations have been made with a French curve. This is a somewhat subjective method, but is justified by the fact (see Table 13 and fig. 33) that the experimental results have been independent of heating time.

This procedure can be applied to the theoretical curves of fig. 33. For a 3 minute exposure the curves should be imagined to start at 1.5 minutes (2 minutes with electric calibrations). Reasonable extrapolation back to zero time will not introduce an error of more than 0.4%, and smaller errors with shorter heating times.

These conclusions have been tested by electric heating runs in which the heat input per gm was divided between the central element and baffle in various proportions, and in which two times of heating were used. The observed changes in balance point of the bridge, in ohms per joule supplied to the central element, are given in table 11. The column headed C represents heating of the centre alone. The variations in the range +10% to -10% are probably not significant.
Table 11.

<table>
<thead>
<tr>
<th>Excess heating of central element $100(1-\lambda)/\lambda$.</th>
<th>$\lambda$</th>
<th>$+20%$</th>
<th>$+10%$</th>
<th>$0$</th>
<th>$-10%$</th>
<th>$-20%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta r/J$ in (50 sec)</td>
<td>639.8</td>
<td>643.2</td>
<td>652.2</td>
<td>655.2</td>
<td>658.4</td>
<td>648.7</td>
</tr>
<tr>
<td>(2 min.)</td>
<td>652.6</td>
<td>644.5</td>
<td>654.1</td>
<td>654.5</td>
<td>657.1</td>
<td>646.1</td>
</tr>
<tr>
<td>Mean %</td>
<td>98.7</td>
<td>98.3</td>
<td>99.7</td>
<td>100.0</td>
<td>100.4</td>
<td>98.9</td>
</tr>
</tbody>
</table>

Representative temperature records from electrical and irradiation runs are shown in figs. 29 and 30. The bridge was brought back to the same degree of imbalance after the heating period, in the same way as in figs. 18 and 19. Heating (electrical or by irradiation) starts at A and ends at B. Extrapolations to the mid time are shown. The last run in fig. 30 is most exceptional in that it suffers from apparent curvature just before the irradiation, and two extrapolation lines are shown. The mean result was used.
6.3. Deviations from Ideal Geometry.

Before giving the results it is necessary to consider the relationship between the measurements of ionization and energy absorption. The intention was that each should approach as near as practicable to the ideal, in which the energy absorption is measured at a point at the centre of a block of carbon, and the ionization is measured in an infinitesimal cavity at the same point. The finite size of the absorbing element and of the ionization chamber, and the finite cavities in the block, introduce disturbances whose importance must be estimated.

Additional carbon discs were attached to the top and bottom of the carbon chamber to increase its thickness to 5.8 cm., the same as the calorimeter block. The essential dimensions of the calorimeter and chamber are shown in fig. 31, for quick comparison.

The diameter of the central element is the same as that of the collecting volume of the chamber. Non-uniformity of the radiation in a lateral direction should affect each equally, except for the slightly greater air volume at the full radius of the chamber.
Fig. 31

Scale 1/1
Dimensions in mm.

Calorimeter

Chamber
To allow for this flattening filters were used (except at 14 MeV). In all cases the intensity at a radius of 1.5 cm was within 0.5% of that at the centre.

The density of the carbon used in the two units differed by less than 1%. The intensities at the centre should differ by less than 0.2%. The heating coils cause negligible attenuation even at 300 kV.

The finite thickness of the central element causes some variation in energy absorption across it. The worst case is likely to be during irradiation by cobalt at short distance. Expressing the attenuation as \( \frac{f^2}{(f+x)^2} \), an effective value for \( \mu \) in carbon can be found from depth dose data in water and is 0.073 cm\(^{-1}\). Usually the centre of the calorimeter was 50 cm from the source. With these factors the average energy absorption throughout the element is 0.07% greater than that at the centre. Even at 300 kV and 43 cm the difference is only 0.12%.

The effects of the cavities are rather more complex. Assume to begin with that the radiation is all travelling along the axes of the blocks. To reach
the central element of the calorimeter the radiation passes across a cavity 2mm wide, and is therefore more intense than it should be by a factor $e^{+0.2\mu}$.

The ionization chamber can be divided into 3 compartments a), b) and c) (see fig. 32). The effective point of measurement with a cavity chamber is the centre of the cavity (Burlin 1959, Kondo and Randolph 1960). The radiation reaching the centre of a) is too intense by a factor $e^{+0.25\mu}$, and therefore the ionization is also too great by this factor. For b) the factor is $\sqrt{\frac{(f - 0.15)^2}{f^2} \cdot e^{-0.4\mu}}$, $f$ being the focal distance of the centre. For c) it is $\frac{f^2}{(f + 0.15)^2} \cdot e^{-0.3\mu}$. The combined factor for (b+c) is almost exactly $e^{+0.2\mu}$.
Only compartment a) has a different factor from that of the calorimeter, the nett excess being \( e^{0.05\mu} \). With \( \mu = 0.073 \, \text{cm}^{-1} \) this comes to 0.37\%. However, compartment a) is only 29\% of the whole volume, so that the ionization is too large by 0.1\%.

If scattered radiation is allowed for the problem becomes much more complicated. The presence of a cavity in a scattering medium diminishes the scattered radiation besides enhancing the primary, so that the effect of a cavity on the intensity at the centre is smaller than would be expected if the primary radiation alone were considered. This has frequently been confirmed experimentally, an example being the measurements reported here in Section 6.8. The cavities in the calorimeter and chamber are such that a scattered ray reaching the centre crosses the same width of cavity in both cases. There is therefore reason to believe that scattered radiation will not worsen the difference between the two units.

The chamber and calorimeter were irradiated under similar conditions, that is to say with the same quantity of absorbing material in the path of the
radiation (1.0 mm aluminium and 5.3 cm celotex). The exact equivalence of the absorbers used was checked experimentally. Back scattering was not identical but is very small with megavoltage radiation. Even at 300 KV the extra contribution from the bottom of the calorimeter box was found to be only 0.2%.

In each of these respects the calorimeter and chamber are measuring the same intensity of radiation to an accuracy of about 0.1%, and a reasonable value of the standard error to allow for all these effects is ± 0.3%.

This approach is different from that of Reid and Johns (1961). They attempted to measure the energy absorption and ionization due to a beam of radiation with only an infinitesimal amount of attenuation and scattering. Consequently they had to apply a number of complex corrections for attenuation in the baffle and the walls of the ionization chamber, and scattering from the stem of the chamber. The approach used here eliminates the need for these corrections, at the expense of giving information about radiation containing a considerable scattered
component instead of about the undegraded primary beam. Further comparisons with the work of Reid and Johns will be made later (Sections 6.6, 6.7).

6.4. Results.

Table 12 gives a list of the experiments made with the carbon calorimeter; each variant of the experimental conditions is given a separate number.

On each occasion 3 kinds of measurement were made - ionization, energy absorption and electric calibration of the calorimeter. The temperature in the calorimeter was measured from time to time by altering the selector switch in the junction box (Section 3.1. and fig. 8). This is necessary since the sensitivity varies slightly with temperature due partly to the properties of the thermistors (Section 3.2.1. equation 11) and partly to the variation of the
<table>
<thead>
<tr>
<th>Number</th>
<th>Date</th>
<th>Location</th>
<th>Radiation Source</th>
<th>Field size at calorimeter</th>
<th>Focal distance to calorimeter</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.9.60</td>
<td>Hammersmith</td>
<td>L.A. 7.5MeV</td>
<td>7.2x7.2</td>
<td>65 cm.</td>
<td>No celotex used</td>
</tr>
<tr>
<td>2</td>
<td>19-20.</td>
<td>Thomas's</td>
<td>Cobalt</td>
<td>13 x 13</td>
<td>90</td>
<td>2 opposed beams</td>
</tr>
<tr>
<td>3</td>
<td>11.60</td>
<td>&quot;</td>
<td>&quot;</td>
<td>10 x 10</td>
<td>50</td>
<td>One beam</td>
</tr>
<tr>
<td>4</td>
<td>26.2.61</td>
<td>Hammersmith</td>
<td>L.A. 7.5MeV</td>
<td>7.4x7.4</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>11.3.61</td>
<td>Bart's</td>
<td>L.A. 14MeV</td>
<td>8 x 8</td>
<td>103</td>
<td>200 pps</td>
</tr>
<tr>
<td>6</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>400 pps</td>
</tr>
<tr>
<td>7</td>
<td>15.4.61</td>
<td>Bart's</td>
<td>L.A. 13MeV</td>
<td>11 x 11</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot; 4.2MeV</td>
<td>11 x 11</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>&quot;</td>
<td>&quot;</td>
<td>13MeV</td>
<td>9 x 10</td>
<td>203</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Cobalt</td>
<td>11 x 11</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>6-7.4.61</td>
<td>Hammersmith</td>
<td>300 KVP</td>
<td>4.6 cm</td>
<td>43</td>
<td>Smaller Baffle</td>
</tr>
</tbody>
</table>
specific heat of carbon with temperature. Both effects cause the sensitivity to fall with rising temperature, by 0.67% and 0.44% per degree respectively.

The alignment of chamber and calorimeter in the beam were checked radiographically. With Cobalt gammas and 300 KVP radiation flattening filters were placed on the lid of the calorimeter box (and on the dummy lid used with the chamber), and the radiographs also checked that the filter was properly aligned with the carbon.

No allowance has been made for any direct effect of the radiation on the thermistors. Compared with water, the lower specific heat of carbon increases the rise of temperature by a factor of 6 per unit of energy absorbed. As the effect was nonexistent or very small for irradiation of water, it can safely be neglected when carbon is used. This might not, however, be true at 300 K.V.
Experiment 2 was exceptional in that the double-headed cobalt unit at Thomas's allowed two opposed beams to be used at once. A flattening filter was included in each beam.

To give all the results of each experiment would take up an excessive amount of space. As an example the results of experiment 10 will be given in detail and the others summarized. Experiment 11 will be treated separately in Section 6. as it was considerably different from the others. No. 10 is interesting because the dose rate of 65 roentgens/min at the element was the lowest used, and so it shows the capabilities of the method. Cobalt gamma radiation has the further advantage over X rays that the intensity is constant, and the results are not complicated by possible variations in the sensitivity of a monitoring chamber.
Ionization measurements were made before and after the series of calorimetric runs, and the results agreed exactly. Exposures in the range 15 to 70 seconds were made. When plotted against the time of the exposure, the readings lay on a straight line cutting the time axis at -0.4 secs. This was added to all the exposure times, and the measured ionization was 52.3 divisions on the Baldwin-Farmer meter in 70.4 secs, or 0.743 divs/sec. There is an uncertainty in reading the meter of ±0.1 div. or 0.2%. Other factors were 760.9 mm Hg, 21.5°C, 52% relative humidity.

The calorimeter was placed so that the carbon absorber occupied the same position as the chamber. This could be done to an accuracy of one mm, giving an uncertainty of ±0.3% in intensity at 60 cm f.d. The results of the 9 irradiations made are given in Table 13. Most of the temperature records are in fig. 30.
Table 13.

**Cobalt Irradiations.**

<table>
<thead>
<tr>
<th>Exposure Time, Secs.</th>
<th>Change of resistance ohms.</th>
<th>$\frac{\Delta r}{t + 0.4}$ x 10^{-4}</th>
<th>C.F. for temperature</th>
<th>$\frac{\Delta r}{t + 0.4}$ corrected x 10^{-4}</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>3.65</td>
<td>605</td>
<td>1.005</td>
<td>608</td>
</tr>
<tr>
<td>60</td>
<td>3.71</td>
<td>615</td>
<td>&quot;</td>
<td>618</td>
</tr>
<tr>
<td>30</td>
<td>1.91</td>
<td>628</td>
<td>1.006</td>
<td>632</td>
</tr>
<tr>
<td>30</td>
<td>1.93</td>
<td>635</td>
<td>&quot;</td>
<td>639</td>
</tr>
<tr>
<td>45</td>
<td>2.88</td>
<td>635</td>
<td>&quot;</td>
<td>639</td>
</tr>
<tr>
<td>75</td>
<td>4.54</td>
<td>602</td>
<td>&quot;</td>
<td>608</td>
</tr>
<tr>
<td>90</td>
<td>5.61</td>
<td>622</td>
<td>&quot;</td>
<td>628</td>
</tr>
<tr>
<td>120</td>
<td>7.49</td>
<td>622</td>
<td>&quot;</td>
<td>628</td>
</tr>
<tr>
<td>180</td>
<td>10.93</td>
<td>607</td>
<td>&quot;</td>
<td>611</td>
</tr>
</tbody>
</table>

The mean is $0.0623 \pm 0.0004$ (standard error) ohms/sec. There is no sign of any variation with exposure time, indicating that the method of extrapolation used is satisfactory.

Electric calibration runs are given in Table 14. The last 4 of these were made immediately after the irradiations. The remainder were made on the previous day, between irradiations with the 14 MeV accelerator.
Table 14.
Electric Calibrations.

| Current mA | Time Secs. | $i^2Rt$ Joules x10^-5 | change of resistance ohms | C.F. for temperature | $\Delta r/i^2Rt$ Mean  

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7945</td>
<td>33.6</td>
<td>1156</td>
<td>7.34</td>
<td>1.007</td>
</tr>
<tr>
<td>1.794</td>
<td>60.0</td>
<td>2062</td>
<td>13.30</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.794</td>
<td>90.0</td>
<td>3093</td>
<td>19.9</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.794</td>
<td>39.0</td>
<td>1340</td>
<td>8.58</td>
<td>1.008</td>
</tr>
<tr>
<td>1.794</td>
<td>55.3</td>
<td>1901</td>
<td>12.23</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.793</td>
<td>103.0</td>
<td>3537</td>
<td>23.04</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.782</td>
<td>29.1</td>
<td>2405</td>
<td>15.35</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.782</td>
<td>60.2</td>
<td>4976</td>
<td>32.30</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.781</td>
<td>90.0</td>
<td>7434</td>
<td>47.9</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.3235</td>
<td>25.0</td>
<td>467.9</td>
<td>3.09</td>
<td>1.007</td>
</tr>
<tr>
<td>1.3235</td>
<td>60.0</td>
<td>1123</td>
<td>7.32</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.7925</td>
<td>34.0</td>
<td>1167</td>
<td>7.55</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.7915</td>
<td>60.0</td>
<td>2056</td>
<td>13.27</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Mean 650.5 $\pm$ 1.8 ohms/Joule.
There is no indication of any variation with time. However, the range of times is rather small. Fig. 3· contains the calibration runs done for experiment 4 and shows clearly that the results are independent of time.

It should not be necessary to do electrical calibrations each time. However, the correction for varying temperature is theoretical and may not be absolutely accurate, and I thought it best to calibrate on each occasion.

Table 15 summarizes the results of experiments 1 - 10. The standard errors in columns 3 and 5 relate solely to the spread of the observations, except for column 5 for experiments 4, 5, 6 and 7.

In experiment 4 the calorimetry runs were done in two groups with ionization runs between, and the means of the two groups differed by 1.1%. This was probably due to a change in the operating conditions of the machine. The electron beam is bent through a right angle before striking the target, and changes in the energy distribution of the electron beam give rise to changes in the distribution of X rays across the field (Newbery and Bewley 1955). The monitoring
Electric Calibrations - Experiment 4

Fig 33
### Table 15. Radiation corrections for electric irradiations of number 1 calorimeter

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>Electric Calibrations</th>
<th>Irradiations of Calorimeter</th>
<th>% of Corrections for Observation</th>
<th>Result Eqs/cm²</th>
<th>Radiation source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n/J ± s.e. n/div ± s.e. No</td>
<td>Focal Saturation</td>
<td>Stray Humidity at 22°C, 760 C</td>
<td>Cobalt</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>657 3 0.0844 0.0004 13 0.9 0.2 0.2 0.3 92.7</td>
<td>8 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>650.1 0.9 0.0838 0.0003 6 - - 1.7</td>
<td>95.5 0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>650.1 0.9 0.0838 0.0003 6 - - 0.5</td>
<td>94.8 0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>653.5 1.0 0.0820 0.0004 12 0.4 0.2 0.2</td>
<td>91.1 0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>649.9 1.6 0.0808 0.0010 3 - 0.3 0.4</td>
<td>90.5 1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>649.9 1.6 0.0799 0.0008 7 - 0.3 0.4</td>
<td>89.4 1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>650.5 1.8 0.0800 0.0005 3 - 0.2 0.6</td>
<td>89.2 0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>650.5 1.8 0.0802 0.0002 4 - 0.2 0.6</td>
<td>90.1 0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>650.5 1.8 0.0802 0.0001 4 + 0.1 0.7</td>
<td>90.3 0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>650.5 1.8 0.0838 0.0005 9 - - 0.8</td>
<td>94.6 0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cobalt
chamber intercepts a wide beam of X rays, and the relation between the average intensity across the field and the intensity on the central axis can alter a little. Another possibility is a change in temperature of the monitoring chamber. The mean of the two groups of calorimetric runs has been used, and a standard error of 0.4% applied to allow for this source of uncertainty.

In experiments 5 and 6 the field size was rather small and there was an uncertainty of 4 mm in lateral positioning. This introduced an uncertainty of 1% in the relation between energy absorption in the calorimeter and ionization in the chamber; and this has been combined with the variation in the observations.

Experiment 1 is less reliable than the others because several refinements of technique had not been brought into use at that stage. During electric calibrations the potentiometer was not balanced on a dummy circuit before the heating run.
Also the total current to the element and baffle together was measured instead of that to the element alone. During the irradiations no check was made of the effect of small lateral displacements, and in experiment 4 it was found that these could introduce errors of about 1\%.

Column 11 gives the result in ergs per gm of carbon per esu/cc in the carbon chamber, at 760 mm Hg and 22°C. As an example of the derivation of these figures, experiment 1 gave 0.0844/657 Joules per division on the Baldwin-Farmer. The sensitivity of the Baldwin-Farmer was 0.2061 volts/div., the capacitor was 6975 pf and the volume of the chamber 3.085 cm$^3$. This gives 1,397 esu/cc per div. The mass of the calorimeter element was 9.800 gm. The chamber was 3 mm further from the target than the calorimeter, and the ionization must be increased by 0.9\%. These
Column 12 includes all the uncertainties listed in Table 16. The item "ionization in chamber versus monitor reading" needs further comment. This type of measurement is not given separately in Table 15, but is combined with the measurement of energy absorption against the monitor reading. Usually the standard error of these measurements was small, about 0.2%. With cobalt the error is solely that of reading the meter. Experiment 7 was exceptional in that ionization runs done before and after the calorimetric runs differed by 1.7%; the mean value was used with a standard error of 0.6%.

The stray radiation reaching the block containing the control thermistor was measured with photographic films. A dummy block consisting of 5 discs with 4 films sandwiched between them enabled the distribution of absorbed dose to be measured. The mean dose throughout the block was found to be only slightly greater than the dose at
the centre. Consequently many of the estimates were made with an ionization chamber, 0.1% being added to allow for the non-uniformity. At 300 KVP the varying response of film with X ray energy made it necessary to rely entirely on chambers.

Corrections for saturation were estimated from fig. 15, and for humidity from Barnard, Aston and Marsh (1960).

The results of Table 15 fall naturally into 3 groups corresponding to the 3 qualities of radiation. The agreement within each group is good, provided experiment 1 is omitted. These results have been combined in Table 17, omitting experiment 1, and weighting the others by the inverse of the squares of the standard errors. The standard error for this purpose does not include the fixed error of 0.5% since this is constant for all the experiments; it has however been included again after the weighting process.
Table 16.

**Standard Error of Measurement of ergs/gm per esu/cc.**

**Fixed Errors common to all measurements.** ±%

<table>
<thead>
<tr>
<th>Error Description</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of the Chamber</td>
<td>0.2</td>
</tr>
<tr>
<td>Saturation of the chamber</td>
<td>0.1</td>
</tr>
<tr>
<td>Voltage calibration of electrometer</td>
<td>0.2</td>
</tr>
<tr>
<td>Calibration of capacitor</td>
<td>0.1</td>
</tr>
<tr>
<td>Heat generated in heater leads</td>
<td>0.2</td>
</tr>
<tr>
<td>Extrapolation of cooling curves</td>
<td>0.2</td>
</tr>
<tr>
<td>Equivalence of calorimeter and chamber</td>
<td>0.3</td>
</tr>
<tr>
<td>Root Square Sum</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Variable Errors.**

<table>
<thead>
<tr>
<th>Error Description</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance - ± 1mm</td>
<td>0.1 - 0.4</td>
</tr>
<tr>
<td>Stray radiation at control block</td>
<td>0.2</td>
</tr>
<tr>
<td>Ionization in chamber versus monitor reading</td>
<td>0.2 - 0.6</td>
</tr>
<tr>
<td>Irradiations of calorimeter - spread of observations</td>
<td>0.2 - 0.6</td>
</tr>
<tr>
<td>Electric calibration - spread of observations</td>
<td>0.1 - 0.5</td>
</tr>
</tbody>
</table>
Table 17.

<table>
<thead>
<tr>
<th>Radiation Source</th>
<th>Effective Energy</th>
<th>Erps/gm of carbon esu/cc at 22°C, 760mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt γ</td>
<td>1.25 MeV</td>
<td>95.1 ± 0.6</td>
</tr>
<tr>
<td>8 MeV L.A.</td>
<td>2.6</td>
<td>91.1 ± 0.8</td>
</tr>
<tr>
<td>14 MeV L.A.</td>
<td>5.2</td>
<td>90.16 ± 0.5</td>
</tr>
</tbody>
</table>

The effective energy referred to in column 2 is a crude way of representing the spectrum by a single energy. A fuller treatment of the spectrum is given in Section 6.6.

6.5. Derivation of W and Stopping Power Values for cobalt.

The results for cobalt radiation gives a value for the product \( W_S m \) which can be compared directly with theory and with other measurements.

\[
W_S m = 95.1 \times \frac{273 \times 0.001223 \times 4.803 \times 10^{-10}}{295} \times \frac{1.602 \times 10^{-12}}
\]

\[
= 34.11 \pm 0.21 \text{ e } - \text{v in carbon per ion pair in air.}
\]

This is 0.1% less than the figure of Reid and Johns (1961) Table 6.
The value for \( \bar{S}_m \) used by Reid and Johns was taken from a draft of a revised version of NBS Handbook 62 which has not been published. The latest published figures are those of Handbook 78 Table 8.6., which include the Spencer-Attix modification.

\( \Delta = 0.6\text{cm} \) is appropriate for Reid and Johns and \( \Delta = 0.3\text{cm} \) for this thesis. Alternatively the stopping powers given in fig. 2 of the thesis can be used, with the same modification. Values of \( W \) derived in this way are given in Table 18.

**Table 18.**

<table>
<thead>
<tr>
<th>Author</th>
<th>( e-v ) in carbon ion pair in air</th>
<th>( \bar{S}_m ) NBS 78, Thesis</th>
<th>( W ) NBS 78 Thesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reid and Johns</td>
<td>34.15</td>
<td>1.020</td>
<td>33.47</td>
</tr>
<tr>
<td>Bewley</td>
<td>34.11±0.21</td>
<td>1.021</td>
<td>33.39</td>
</tr>
</tbody>
</table>

Thus, using the stopping powers from fig. 2 the measurements reported in this thesis give

\[ W = 33.8 \pm 0.2. \] The NBS stopping powers give

\[ W = 33.4 \pm 0.2. \] This is 0.2% less than the result of Reid and Johns.
6.6 **W and Stopping Powers for the accelerators.**

To derive similar information from the measurements with the accelerators, it is necessary to know the spectra of the radiations used. The possible influence of scattered radiation also needs looking into for all the radiations used, including cobalt.

6.6.1 **Scattered Radiation.**

The importance of scattered radiation can be estimated easily in the case of cobalt gamma radiation. The problem is whether the relative stopping power of carbon to air at the chamber is modified by the presence of softer scattered radiation.

The amount of scattered radiation can be estimated from tables of depth doses in water. The scattering conditions at the centre of the carbon block are nearly the same as those at a point 4.4 cm deep in water at the centre of a field 65 cm² (see Section 5.2). At 60 cm S.S.D. the depth dose at this point is 78%, of which 68% is due to the primary radiation (Kemp and Cohen, 1961). Scattered radiation is therefore 13% of the total at that point. The energy of the scattered radiation can be estimated roughly from the fact that the angle of bipartition of the scattered energy is 37° for 1.25 MeV quanta. This gives $h\nu = 0.84$ MeV. The mean starting energy of the recoil electrons
is $h \nu / \sigma = 0.34$ MeV. $\bar{S}_m$ for the scattered radiation is then 1.011, which is to be compared with 1.003 for the primary radiation. Allowing for the proportion of scattered radiation present, the effect of the scatter on the relative stopping power is $0.13 \times 0.008$ or 0.1%.

A more accurate calculation can be made using the results of Bruce and Johns (1960). These authors calculated the spectra of scattered radiation at points in water exposed to cobalt gamma radiation. From the spectrum of scattered radiation at 5 cm deep the spectrum of starting energies of the recoil electrons can be calculated, from Fig. 4 of NES handbook 62. The mean relative stopping power can then be calculated from equation (6). This has been done, and the scattered radiation was found to increase the value of $\bar{S}_m$ from 1.003 to 1.004.

Similar calculations to the more approximate ones above have been made for x-rays generated at 8 MeV and 14 MeV. With rising energy the mean angle of scatter becomes smaller but the change in energy at a given angle increases, and these effects are roughly equal and opposite. The total quantity of scattered radiation is less, but on the other hand the curve of $\bar{S}_m$ against energy becomes steeper. These effects also
are roughly equal and opposite. The net result is that scattered radiation affects the relative stopping power by about 0.1% at all these energies. This correction is not really of any significance, but has been included for the sake of completeness.

6.6.2 X-ray spectra.

The spectrum of radiation from the 8 MeV machine has been estimated from calculations made by Howard-Flanders for 10 MeV electrons striking a thick gold target (private communication). This has been scaled down to 7.5 MeV and corrected for attenuation in the target (4.75 mm gold) and the flattening filter (7 cm aluminium). The correctness of the spectrum has been tested by narrow beam attenuation measurements in water and lead. Table 19 shows that this spectrum is in satisfactory agreement with the measurements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Depth cm</th>
<th>Transmission %</th>
<th>Observed</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>10</td>
<td>65.5</td>
<td>65.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>43.6</td>
<td>43.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>29.8</td>
<td>29.2</td>
<td></td>
</tr>
<tr>
<td>lead</td>
<td>2</td>
<td>35.0</td>
<td>34.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>12.6</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4.7</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.75</td>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>
The radiation spectrum from the 14 MeV machine has been measured by Ward and Dolphin (1960), who found that the spectrum above 6 MeV agreed with the calculations of Schiff for a thin target. Accordingly I have used the Schiff spectrum, interpolated from data given by Koch and Mott (1959), and corrected for attenuation by 4 mm of gold and 3.7 mm of brass.

These spectra are shown in Fig. 34. The spectra of the number of recoil electrons with a given energy have been calculated from Fig. 4 of NBS Handbook 62, with an allowance for pair production. This multiplied by the energy (i.e., \( T_0 A(T_0) dT_0 \)) is shown in Fig. 35.

Stopping power figures obtained from these spectra, using equation 6 and Fig. 2, are given in Table 20. Allowing for a Spencer-Attix modification of 0.004, values of \( W \) have been calculated for each radiation.

<table>
<thead>
<tr>
<th>Radiation</th>
<th>( \overline{S}/S_m )</th>
<th>( S_m ) including Spencer-Attix modification and scatter</th>
<th>Measured ( \text{Ergs/mg} ) esu/cm</th>
<th>( \frac{W}{\text{esv}} ) \text{ion pair}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt ( \gamma )</td>
<td>1.003</td>
<td>1.008</td>
<td>95.1</td>
<td>33.8 ± 0.2</td>
</tr>
<tr>
<td>8 MeV L.A.</td>
<td>0.983</td>
<td>0.986</td>
<td>91.1</td>
<td>33.1 ± 0.5</td>
</tr>
<tr>
<td>14 MeV L.A.</td>
<td>0.965</td>
<td>0.970</td>
<td>90.16</td>
<td>33.4 ± 0.2</td>
</tr>
</tbody>
</table>
X-ray Spectra

Fig. 34

Intensity vs. MeV

- 7.5 MeV
- 14 MeV
FIG. 35
Spectra of Recoil Electrons

$T_0 A(T_0) dT_0$

$\gamma\cdot Co$

7.5 MeV

14 MeV

$T_0$ vs. MeV
The measured ergs/gm per esu/cc falls steadily with rising energy as expected, in parallel with the fall in stopping power. The result at 8 MeV, however, is a little low. Better agreement would have been obtained by using the mean of experiments 1 and 4 in Table 15, although experiment 1 was rejected for unreliability. Also, the electric calibration for experiment 4 was 3/4 higher than the others, and if this was an error the value of \( W \) would be 33.3. The uncertainty has been increased by 0.2\% to allow for this. In any case, the variation of stopping power with energy over this energy range is confirmed to an accuracy of 2\%.

If the stopping powers given in IRE handbooks 62 and 73 were used, these values would be reduced by 0.4. At 8 MeV \( W \) would then be 32.7 \( \pm \) 0.5. This can be compared with the measurements in water given in Table 10, and will be seen to be in good agreement with the result using ferrous sulphate.

### 6.7 Direct Calibration of Ionization Chambers in terms of Absorbed Dose from Megavoltage Radiations.

The importance of these calorimetric measurements lies in the fact that ionization chambers can be calibrated directly to measure absorbed dose, avoiding uncertainties in \( W \) and \( \frac{S}{m} \).
The procedure is as follows. The carbon chamber is first compared with the calorimeter in the manner already described, using the radiation of interest. It is then a standardised chamber for this particular radiation and can be compared with other chambers. The reference point at which the value of the absorbed dose is needed is the peak of the depth dose curve in water. This can be specified by two parameters, the focal distance and the depth from the surface in electrons per cm². The carbon chamber should be placed at the same focal distance and the same depth. The substandard instrument being calibrated can be exposed in any arbitrary but reproducible way. Variations of pressure temperature and humidity will affect both chambers equally and can be ignored. The great advantage of this method over that advocated by Reid and Johns is that no corrections are needed for attenuation in the walls of the chambers and calorimeter. The absorbed dose is measured under the conditions of interest, namely in a scattering medium representing tissue.

The measurements with the carbon chamber at 8 MeV described in section 5.2 serve as an example. The peak of the depth dose curve in water is at 2 cm. The thickness of carbon to give the same number of electrons/cm² is \(2 \times \frac{1.11}{1.68} = 1.32 \text{ cm.} \)
The depth of carbon to the centre of the chamber was actually 1.5 cm. If one allows for the gap of 2 mm in the chamber this is just right, and in any case if 2 mm of carbon is removed, keeping the chamber at a fixed distance, the ionization changes by less than 0.1%. The substandard chamber is a Baldwin-Farmer exposed in a perspex block. The relative ionizations were 5.29. Hence the absorbed dose in water at 2 cm deep is

\[ 5.29 \times 0.990 \times 1.116 \times 91.1 \times 1.397 = 7.42 \text{ rads/div. in dry air at } 22^\circ \text{C, 760 mm} \]

Where 0.990 corrects from 101.5 to 102 cm f.d.

1.116 = \( \frac{\text{H}_2\text{O}}{\text{H}^4}\)C

91.1 = ergs/gm carbon per esu/cc (Table 17)

1.397 = esu/cc per div.

The chamber used to check the x-ray output from the 14 MeV accelerator has been calibrated in a similar way.
6.8 Measurements at 300 KVP.

At 300 KVP ionisation chambers can be calibrated in roentgens by means of a free air chamber. A comparison of energy absorption in carbon with the exposure dose in roentgens at the same point can in principle give a value of which is independent of relative stopping power values.

There is a fundamental difficulty in that the energy absorption in carbon per roentgen is constant only above 200 KeV quantum energy. Below this the energy absorption begins to fall off, in a similar way to, but more steeply than, the energy absorption in water shown in Fig. 1. It has fallen by 1% at 150 KeV and by 7% at 100 KeV.

Unless the spectrum at the point of interest is measured accurately it is best to use the greatest possible amount of filtration and to reduce the amount of scattering material to a minimum. The filtration can be increased only at the expense of reducing the intensity, and if the calorimeter block is made very small the thermal time constant becomes inconveniently short.

As a compromise a filter of 0.4 mm Sn, 0.46 mm Cu and 1 mm Al was used, giving a h.v.l. of 3.2 mm Cu. In addition, a brass flattening filter, 0.5 mm thick at the centre, was used to give a uniform dose distribution across the mid-plane of the calorimeter. The centre of the calorimeter was at 43 cm
The central element of the calorimeter was the same as that used at the higher energies, but the baffle was smaller and measured 4.2 cm diameter by 3 cm high. The control thermistor was in a similar block. In other respects the calorimeter was identical to that already described.

The exposure dose was measured with a Baldwin-Farmer chamber inserted into a similar block of carbon and exposed in a similar geometry. The chamber was compared with another which had been calibrated at the NRL, and whose correction factors were 1.03, 1.02 and 1.03 at h.v.l.s of 0.5, 1.0 and 2.0 mm Cu respectively. The factor has been taken as 1.03 ± 1% for the radiation present in the calorimeter.

12 irradiations of the calorimeter were made, divided into two groups with ionization measurements between. Electronic calibration runs were also performed. The temperature inside the calorimeter could not be measured as the room temperature was too high; however, this did not vary by more than 1°C and no correction for the temperature has been made.

The result of the measurements, before making any corrections (except for humidity), was 90.1 ergs/gm of carbon per roentgen.
6.8.1 Corrections.

The stray radiation at the control block amounted to 0.2% of that in the irradiated one. This low figure was achieved only by including a thin sheet of lead in the calorimeter which intercepted radiation scattered from the irradiated block.

The Baldwin-Farmer chamber has an internal diameter of 6 mm, and a cavity of this size in the carbon block must have some influence on the exposure dose. This was investigated by measuring the ionization when the chamber was placed at the centre of cavities of varying diameter. The geometry and results of the measurements are shown in Fig. 36. Allowing for the wall of the chamber being $\frac{1}{2}$ mm thick, the exposure dose in the absence of a cavity might be found by extrapolating back to a cavity 1 mm in diameter. Two extreme methods of doing this are shown. It is most unlikely that the truth lies beyond these extremes.

Accordingly, the exposure dose in the absence of a cavity is $0.994 \pm 0.01$ times the measured value. The calorimeter also contains a cavity 2 mm thick all round the central element. If the effect of this is the same as that of a cavity 4 mm diameter at the centre, the correction for the calorimeter would be almost the same as that for the chamber and both could be neglected. On the other hand, an upper limit can be found
FIG: 86

EFFECT of CAVITY on
EXPOSURE DOSE.

IONIZATION

103
102
101
100
99
98

Diameter of Cavity, D.

2 4 6 8 10 12 14 16 18 20 mm

RADIATION

D
by the method of section 6.3, taking account only of the cavity above the central element. The centre of the calorimeter is equivalent to a point 2.3 cm deep in water in a field 6.35 cm diameter. Tables of depth dose data give an effective absorption coefficient (after allowing for the inverse square law) of 8.5% per cm, or 13% per cm in carbon. A gap 2 mm wide would enhance the intensity by 2.6% on this basis. However, this degree of enhancement is three times that shown in Fig. 36, which illustrates the remark in section 5.2 that lack of scattered radiation from the cavity largely counteracts the enhancement of radiation arising beyond it. A reasonable allowance for the combined effect of the cavities in the two blocks is zero ± 1%.

The most important correction is that concerning the spectrum of the radiation and the energy absorbed by the materials present in the calorimeter.

Primary and scattered spectra of x-rays generated by 280 Kvp radiation, 3.1 mm Cu h.v.i., have been measured by Corneak et al. (1958). They measured the spectrum of scattered radiation in water at various depths and field sizes, and found that the shape of the spectrum was not sensitive to changes in these factors. Accordingly their figures for 2 cm deep in
water, 300 cm², have been used for the spectral shapes, but
the proportion of scattered radiation present has been calculated
from depth dose tables of Johns et al. (1961). It may be
thought that depth dose tables are not strictly applicable to
the calorimeter block since the latter is an isolated object
and no scattered radiation can arise outside it, but the error
due to this is very small. Interpolation in table 3.5.1
shows that, at 2.3 cm deep in a field 6.35 cm diameter, 66%
of the radiation is primary and 34% is scatter. The spectra
of Cormack et al. are given in terms of photons. They were
converted into rads in water to find the weighting factors
needed to give the proportion 66/34, and the result is shown
in fig. 37. This was then converted into roentgens for the
calculations of energy absorption.

The foreign matter present in the central element
of the calorimeter was listed in section 6.1. The lead equiv-
alent of the thermistor in lead glass was estimated radiographically
as 2.5 mg. The rest of the mass was assumed to be Fe₂O₃, and
the Eureka heater was also taken as Fe. The weight of the
element was 9.8 gm. This gives the following fractions of
foreign matter:

<table>
<thead>
<tr>
<th>Element</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>2.5 x 10⁻⁴</td>
</tr>
<tr>
<td>Fe</td>
<td>7.3 x 10⁻³</td>
</tr>
<tr>
<td>Pt</td>
<td>3.0 x 10⁻⁴</td>
</tr>
</tbody>
</table>
FIG 37
PHOTON SPECTRUM AT CALORIMETER

QUANTUM ENERGY

NUMBER OF PHOTONS

TOTAL
SCATTER
PRIMARY

200 KeV
300
The energy absorption in each of these materials (and in carbon) relative to the energy absorption in air has been estimated from

\[
\int_0^{E_{\text{max}}} \frac{r(E) \frac{dE}{\mu_{\text{air}}} \, dE}{\frac{dE}{\mu_{\text{air}}}}
\]

where \( r(E) \, dE \) is the number of roentgens between energies \( E \) and \( E + dE \) and \( \mu_{\text{air}} \) is the real absorption coefficient. In the case of platinum a correction was applied since the platinum wire was thick enough to absorb most of the softer radiation falling on it and the energy absorption was less than it would have been if the platinum had been uniformly dispersed. The total energy absorbed, compared with that absorbed by the same weight of air, was found to be made up of:

<table>
<thead>
<tr>
<th>Material</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.968</td>
</tr>
<tr>
<td>Lead</td>
<td>0.023</td>
</tr>
<tr>
<td>Iron</td>
<td>0.007</td>
</tr>
<tr>
<td>Platinum</td>
<td>0.022</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.020</strong></td>
</tr>
</tbody>
</table>

There is considerable uncertainty attached to this figure. It is sensitive to changes in the low energy end of the spectrum. Also only that part of the platinum wire lying within the central element has been included. The wire was 5.5 cm long, 3 cm of which lay within the element, and some of the heat produced in the outer part may have been conducted to the element. If the whole wire were included the result would be nearly 2% greater. However, the error is most unlikely to exceed 3%, and a standard error of 1.5% will be used.
The energy absorbed by 1 gm of air exposed to one roentgen is 87.7 ergs if \( W = 34.0 \). The value of \( W \) found by this experiment is therefore:

\[
\frac{1.002 \times 90.1 \times 34.0}{1.020 \times 87.7} = 34.3 \pm 0.8 \text{ e = w/ion pair.}
\]

The standard error is made up of:

- Calibration of Baldwin-Parmer chamber . . . . . . 1%
- Comparison of ionization and energy absorption 0.6%
- Effect of cavities . . . . . . . . . . . . . . . . . . . . . 1%
- Effect of spectrum . . . . . . . . . . . . . . . . . . . . . 1.5%

Root square sum \( \pm 2.2\% \)

6.8.2 Possible improvements in accuracy.

The largest source of uncertainty lies in the presence of soft radiation with materials of both high and low atomic number. It would be a great advantage if a thermistor were obtainable with leads made of a material other than platinum, and not embedded in lead glass. But even then the real absorption coefficient of carbon relative to air is changing rapidly at the low energy end of the spectrum, and rather harder radiation would be valuable. 400 KVP radiation would be significantly better than that generated at 300 KVP provided the free air chamber is reliable at this energy. To reduce the uncertainty due to the
cavities an "air-walled" chamber should be made of similar design to the carbon chamber described in section 4.2. With these precautions it would be possible to obtain an accurate estimate of $W$ independently of stopping-power ratios.
7. Conclusions

The measurements with the carbon calorimeter have shown that it is possible to make precise measurements of the energy locally absorbed from megavoltage radiation by a material not too dissimilar from tissue. The measurements with the carbon chamber have shown that this absorbed dose can be accurately compared with the ionization per unit mass of gas in a small cavity at the same point.

On the other hand, the measurements of energy absorption in water were less reliable. The causes of this have not been fully explained, but probably measurements in a free liquid are inherently less reliable than those in a solid owing to the difficulty of preventing convection. Corrections for radiochemical reactions are another source of difficulty. However, in spite of these problems the measurements in ferrous sulphate solution are in excellent agreement with those in carbon at 6 MeV. In the course of this work it was found necessary to measure the heat of reaction between dilute solutions of hydrogen peroxide and ferrous ammonium sulphate. The result, $71.3 \pm 2.5$ Kcal/mole, is in excellent agreement with heats of formation of the ionic species given in NBS circular 500. The very sensitive equipment developed for this work enabled the reaction to be studied at
a much higher degree of dilution than in previously published measurements.

Another point that occurred during this work concerns the effect of a phantom material on the ionization in a thimble chamber used to measure megavoltage x-rays. Several such materials are in common use as substitutes for water or tissue. Although they may give the correct distribution of radiation, it was found that they give rise to variations of a few per cent in the absolute ionization in a chamber immersed in them.

The microcalorimetric equipment, using thermistors in an AC bridge, has proved most satisfactory in use. Its sensitivity (about $2 \times 10^{-6} \, \text{°C}$) is at least as great as others that have been reported, and probably could be increased further should that be needed. It is sufficiently rugged to be wheeled from room to room and to be transported between hospitals. There was no clear evidence of any direct effect of radiation on thermistors, other than by heating.

The polarization correction for relativistic electrons in condensed media has been confirmed by measurements using the carbon calorimeter with megavoltage x-rays and using the Fricke Dosimeter with 8 MeV electrons. The magnitude of the effect is in agreement with the calculations of Sternheimer. On the
other hand, measurements with photographic films suggested that no such effect exists. The paradox can be explained partly by the possible presence of some soft x-rays and partly by the fact that the film measures energy deposition in silver halide rather than in water. It is suggested that film is not an ideal method of measuring electron depth dose distributions in water.

The only detailed report which has been published up to the present of an accurate comparison of ionisation with energy absorption in materials of low atomic number is that of Reid and Johns (1961). Their figure for carbon irradiated by cobalt gamma rays is 54.15 e·v in carbon per ion pair in air. My figure of 34.11 ± 0.2 agrees remarkably well with theirs, in spite of important differences in method.

If this result is used to calculate the value of \( W \) for air (e·v per ion pair), the uncertainty in the stopping power factor is considerably larger than the uncertainty in the relation between ionisation and energy absorption. Stopping powers given in NBS handbook 78 lead to \( W = 33.4 ± 0.2 \), while those of Fig. 2 of this thesis lead to \( W = 33.8 ± 0.2 \). The most accurate value measured by methods not requiring stopping power factors is that of Bay et al (1957) (see Table 1), who found \( W = 33.7 ± 0.3 \).
An attempt was made to avoid the stopping power problem by making a measurement at 300 kVp, in which energy absorption was compared with the exposure dose. However, the presence of platinum leads and lead glass attached to the thermistor made the accuracy rather poor. If thermistors can be obtained which do not include these materials an accurate measurement should be possible, particularly if x-rays generated at 400 kVp could be used.

The close agreement between my result and that of Reid and Johns lends weight to their argument that the time has come when ionization chambers for use with megavoltage x-rays should be calibrated directly in terms of absorbed dose using a calorimeter, instead of in terms of exposure dose as is done at present. The work reported in this thesis shows that it is not necessary to make complicated corrections for attenuation of the radiation in the manner of Reid and Johns. Ionization and energy absorption can be measured in a block of tissue-like material (carbon). Subsidiary instruments can then be compared with the directly calibrated carbon chamber, also at a depth in a scattering medium. As an example ionization chambers used for calibrating the x-ray beam from 6 and 15 MeV accelerators have been standardised in this way.
ACKNOWLEDGEMENTS

I would like to thank Dr C.A.P. Wood, Director of the M.R.C. Radiotherapeutic Research Unit, for permission to carry out this research. I am grateful to my supervisor, Dr L.H.S. Clark, and to Mr C.R. Newbery and Dr J.F. Fowler for encouragement and helpful advice. I am indebted to the staff of the Physics and Radiotherapeutic departments of St. Bartholomew’s and St. Thomas’s hospitals for permission to use their radiation sources, and particularly to Professor J. Rothblat, Mr A.L. Bradshaw and Mr P.R. Purser for help with the measurements made at these centres. I am most grateful to Dr M.E. Ebert for his help and advice on the subject of radiation chemistry. Dr Ebert prepared the solutions of ferrous ammonium sulphate and formic acid and made all the measurements of optical density. I am also most grateful to Miss J.A. Stevenson, who made the measurements with films reported in section 5.1.1, helped with many other measurements, and prepared some of the diagrams. I am indebted to Mr G. Harding for building the electronic apparatus, much of which was designed by him. I would like to thank my wife for typing most of the thesis. I am also deeply indebted to many members of the Radiotherapeutic Research Unit, and especially to Mr V. Dickinson, for help in constructing apparatus, making measurements, and preparing this thesis.
B. REFERENCES

Adams, G.D. (1957) Radiology 69, 867


Attix, P.H., Berger, M.J., Gross, W., Rooseth, W.C., and White, G.N. Stopping powers for use with cavity chambers, U.S. National committee on radiation protection and measurement, second draft.

Attix, P.H., and Ritz, V.H. (1957) J. Res. N.B.S. 59, 293

Attix, P.H., De la Vergne, L., and Ritz, V.H. J. Res. N.B.S. 60, 235 (1958)


Bakker, G.J. and Segre, E. (1951) Phys. Rev. 81, 469

Barber, W.C. (1955) Phys. Rev. 97, 1071

Barber, W.C. (1956) Phys. Rev. 103, 1281


Bethe, H.A. and Livingstone, M.S. (1937) Rev. Mod. Phys. 9, 245


Doll, J.W. Dolphin, G.W. and Botblat, J. (1953)  
Rad. Res. 9, 589  

Studies in Radioactivity  
Macmillan, New York  

Phys. Rev. 104, 591  

Phys. Rev. 98, 1112  

Brit. J. Radiol. Supp. 9  

Rad. Res. 3, 561  

Rad. Res. 6, 79  


Thesis  

Dolphin, G.W. and Innis, G.S. (1956)  

Emery, G.W. (1956)  

Fano, U. (1946)  

Fano, U. (1954)  

Fermi, E. (1940)  

Done. 11, 133  


Dainton, F.S. and Sutton, H.C. (1953)  

Trans. Farad. Soc. 49, 1022  

Trans. Farad. Soc. 48, 905  

J. Chimie Physique 52, 578  


B.J. Radiol. 29, 370  

Phys. Rev. 70, 44  

Rad. Res. 1, 237  

Phys. Rev. 57, 485
Fricke, H and Morse, S. (1927) Amer. J. Roentgenology 18, 426
Genna, M. S. and Laughlin, J. S. (1955) Radiology 65, 394
Goodwin, P. N. (1959) Rad. Res. 10, 6
Goodwin, P. N. (1960) Radiology 75, 112
Gray, L. H. (1937) B. J. Radiol. 10, 600 and 721
Greening, J. R. (1957) B. J. Radiol. 30, 254


Laughlin, J.S. Beatty, J.W.
Henderson, J. and Harvey, R.A. (1953)


Lindsay, D.D. and Stern, B.E. (1955) Radiology 60, 355

Mather, R. and Segre, E. (1951) Phys. Rev. 84, 191


Milvy, P. Genna, S. Barr, N.
and Laughlin, J.S. (1958)

2nd U.N. Conf. P/744

Murdoch, J. and Stahel, E. (1935)

Nelms, A.T. (1958)


Ovadia, J. Danzker, H. Beattie, J.W.
and Laughlin, J.S. (1955)

Rad. Res. 340, 3 (abstract)

Peisach, M. and Steyn, J. (1960)

Nature 187, 58

Platzmann, R.L. (1955)

Rad. Res. 2, 1

Reid, W.B. and Johns, H.E. (1961)

Rad. Res. 14, 1
Levine, S. and Jaffe, I. (1952)

Schon, M. (1943) Taschenbuch fur chemiker und physiker ch. 26 Ed. D'ans and Lax


Stahel, E. (1929) Strahlentherapie 33, 296

Thompson, T. J. (1952) UGRL 1910


Whyte, G. N. (1957) Rad. Res. 6, 371
Wyckoff, H. O. (1960) J. Res. N. B. S. 64c, 87
Zimmer, K. G. (1954) Zhurnal eks. i teoret. fisiki 26, 367
CONFLICTING views have been expressed regarding the use, in hysterosalpingography, of screen control during the injection of the contrast medium, as opposed to a purely radiographic technique.

Pollock and Preiskel (1951), Moore White (1951), and Marshak, Poole, and Goldberger (1950), prefer fractional injections of contrast medium, using a purely radiographic technique.

Pollock and Preiskel (1951) indicated that a rapid radiographic technique with several films gives as much information as screening with subsequent radiography, and also that better films are obtained with the over-couch tube and Potter-Bucky than with the under-couch tube. These authors, Preiskel and Pollock (1952), recorded that, with their technique and using a 29 inch F.S.D., the average dose received by the ovaries was 1.6-2 r for an 8-film examination.

Osborn (1952) measured the radiation dose received by the ovaries in 14 patients subjected to hysterosalpingography. This author claimed that the average dose to the ovaries was 20 r during screening and 7 r during radiography, and estimated the maximum ovarian dose to be 55 r.

MacGregor and Oliver (1952) measured with small ionization chambers the radiation received by the skin, vagina, and ovaries, using the screening technique. In contrast to Osborn's results, these authors found that the largest doses observed during an examination were 47 r to the skin, 4 r to the vagina, and 6 r to the ovaries. Their technique included screening for 1-2 minutes and two radiographs.

At Hammersmith Hospital the screening technique for hysterosalpingography is used. The factors are as follows:

**Screening.**—82 kilovolts, 3 milliamperes. Maximum aperture 6 cm. square (as measured on the screen). No filter. Focus–table-top distance 53 cm.

**Radiography.**—A.P. 80 kilovolts. 75 milliamphere-seconds. (Lateral, 85 kilovolts, 150 milliamphere-seconds. No filter. Over-couch tube, with focus–table-top distance 82 cm. Standard films and screens with Potter-Bucky.) A considerable voltage drop during exposure was suspected.

The anatomical position of the ovaries was measured in several cadavers, and it was considered that in the average case they lie at a distance of 8 cm. from the table-top with the patient supine, and approximately 4 cm. from the midline. The aperture used during screening never exceeds 6 cm. square as measured on the screen, corresponding to under 5 cm. square at the level of the ovaries. Therefore with this size of aperture the ovaries are not irradiated directly while the uterus is being screened, unless that organ is displaced away from the midline. During the examination, after filling of the uterine cavity has been observed, the fluoroscopic field is moved to each side in turn to observe tubal filling.

**Dose Estimations.**—The dose of radiation delivered by this technique was estimated by taking measurements in a tissue equivalent phantom made of mix D wax, (Jones and Raine, 1949; Jones, 1952). The phantom was 16 cm. deep, corresponding to the thickness of the average patient. The measurements were made with a bakelite–graphite ionization chamber connected to a d.c. amplifier. The chamber was placed in the wax phantom at various depths and distances from the midline, and the radiation received in each position was calculated both under screening and radiographic conditions.

In order to apply these measurements in the phantom to the doses actually received by the patient, the screening time was estimated in a series of 20 unselected patients. By using two stopwatches we measured both the total screening time and the time during which a single ovary was being directly irradiated. The left ovary was chosen for this purpose. It was assumed that the
direct radiation to one ovary would be equal to that received by the other. The results were as follows:

Total Screening Time.—The average total screening time was 1 min. 23 sec. The range was from 39 sec. to 3 min. 24 sec. This rather high maximum was due to the fact that one patient had two examinations performed on the one occasion.

Time of Direct Radiation to the Left Ovary.—The average screening time during which the left ovary was being directly irradiated was 23 sec. The range was from 6 sec. to 48 sec. On the average the left ovary was being directly irradiated for just over a quarter of the total screening time.

In addition to direct radiation each ovary must receive some scattered radiation during screening of the rest of the pelvic cavity. In order to estimate this amount the ionization chamber was placed in the wax phantom at various distances outside the direct X-ray beam. At a point r cm. outside the beam the dose-rate was 18 per cent of its value in the centre of the beam at the same depth. But in actual fact, when the uterus is being screened, the ovaries normally lie more than 1 cm. outside the direct beam; therefore by accepting the scattered dose received by the ovary as 18 per cent, we ensured that this dose was not underestimated. At a point 5 cm. outside the beam the dose-rate was reduced to 3 per cent. This would correspond to the dose received by one ovary while the other ovary is in the direct beam, and is small enough to be insignificant.

RESULTS

1. Under Screening Conditions.—These experiments showed that during screening the radiation to the skin surface in contact with the table top was 9 r per minute, and 1-6 r per minute at the depth of the ovaries. The radiation received by the left ovary was as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Radiation Received</th>
</tr>
</thead>
<tbody>
<tr>
<td>By direct screening of left ovary for 23 sec.</td>
<td>0.6 r</td>
</tr>
<tr>
<td>By scatter, during screening of right ovary</td>
<td>Nil</td>
</tr>
<tr>
<td>for 23 sec.</td>
<td></td>
</tr>
<tr>
<td>By scatter, during midline screening of the</td>
<td>0.2 r</td>
</tr>
<tr>
<td>uterus for 37 sec.</td>
<td></td>
</tr>
<tr>
<td>Therefore the average total radiation received</td>
<td>0.8 r</td>
</tr>
<tr>
<td>by the left ovary during screening</td>
<td></td>
</tr>
</tbody>
</table>

2. Under Radiographic Conditions.—Our present technique involves the taking of two anteroposterior films only, in the majority of cases. In some instances a further film is taken in the lateral position. In the 20 patients studied for the purpose of these calculations, a lateral film was utilized only on 3 occasions.

The wax phantom experiments showed that the dose received by the patient per radiographic exposure, using the factors already mentioned, was as follows:

To the skin surface nearest the tube:

<table>
<thead>
<tr>
<th>Position</th>
<th>Radiation Received</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anteroposterior</td>
<td>4.3 r</td>
</tr>
<tr>
<td>Lateral</td>
<td>1.7 r</td>
</tr>
</tbody>
</table>

To the ovaries:

<table>
<thead>
<tr>
<th>Position</th>
<th>Radiation Received</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anteroposterior</td>
<td>0.45 r to each ovary</td>
</tr>
<tr>
<td>Lateral</td>
<td>1.5 r to uppermost ovary</td>
</tr>
</tbody>
</table>

Thus the average dose of radiation received by one ovary, during an examination involving screening for 1⅛ min. and the taking of two anteroposterior films, was 1.7 r, or 3.2 r when one lateral film was added. The maximum dose received was estimated to be 3.6 r, for a patient whose examination required the taking of four films.

DISCUSSION

In the average case radiography and screening make almost equal contributions to the total ovarian radiation. Thus our combined technique would deliver the same dose as four radiographs, but the former gives much more clinical information.
It may be argued that a homogeneous phantom is not really equivalent to the human body. However, we think that the doses measured in the phantom are very similar to those actually delivered to the patient, as most of the radiation falling on the ovaries passes through the sacrosciatic notches and not through dense bony structures which would absorb the X rays.

Our results are similar to those of MacGregor and Oliver (1952), allowing for the different working conditions and experimental methods.

An aperture of 6 cm. square has been found to be very satisfactory for practical purposes, combined with intermittent screening for a few seconds at a time. This small aperture ensures that the ovaries are not being directly irradiated during the whole screening examination.

The apparatus employed necessitated the use of a screening current of 3 milliampere. We have found this current adequate for hysterosalpingography, uterine contour and tubal filling being readily seen, provided the operator is properly dark-adapted.

We therefore conclude that, by using the screening technique described, no additional radiation hazard is introduced into the examination of hysterosalpingography.

Our thanks are due to Dr. R. E. Steiner and Dr. L. H. S. Clark for their helpful criticism.

REFERENCES

— — and RAINB, H. C. (1949), Ibid., 22, 539.
OSBORN, S. B. (1952), Lancet, 1, 671.
CORRESPONDENCE

Phantom Materials for Use with Megavoltage X-rays

The Editor,

Sir,

I have recently found that the ionization measured with a thimble chamber immersed in commonly used tissue-equivalent phantom materials, using x-rays generated at 8 Mv, varies to a small but significant extent between the different materials used. The measurements were made with a Baldwin—Farmer sub-standard type chamber, at a fixed distance from the target (101.9 cm). The thickness of the phantom lying in front of the chamber was adjusted in each case to bring the ionization to a maximum. The situation is thus typical of an experiment to determine the RBE of megavoltage x-rays. The fact that the ionization varies slightly with the phantom material used would result in corresponding small variations in the reported value of RBE.

The measured ionization (relative to that in mix D) is shown in the upper row of figures in the table.

<table>
<thead>
<tr>
<th>Relative Ionization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix D</td>
</tr>
<tr>
<td>Measured</td>
</tr>
<tr>
<td>Calculated</td>
</tr>
<tr>
<td>Calculated, with correction</td>
</tr>
</tbody>
</table>

† Using the composition given by Lindsay and Stern (1953).
‡ Using the composition given by Jones and Raine (1949).

The calculated figures have been derived as follows, assuming that the phantom forms the wall of the ionization chamber.

The Bragg—Gray relation may be written:

\[ E = J W s \]

or

\[ J = E / W s \]

where \( J \) is the ionization per gram of gas in the chamber, \( W \) is the mean energy required to form one ion pair in the gas, \( E \) is the energy absorption per gram of the wall, \( s \) is the relative mass stopping power of wall to gas.

The ionization is therefore proportional to the ratio \( E / s \). This ratio has been evaluated for x-rays generated at 8 Mv, and for four commonly used phantom materials.

Relative values of \( E \) have been calculated for quantum energies in the range 0.5 to 8 Mev, using N.B.S. Handbook 62 (1957). Figures for \( s \) were taken from N.B.S. Circular 577 (1956). A simple approximation was used to find the effective energy of the recoil electrons corresponding to each
quantum energy; the initial energy was taken as $h\nu_0/\sigma$, and the average energy was taken to be half this. Circular 577 does not include the polarization correction, which is appreciable at these energies. However, this correction does not vary greatly between the four materials considered, and will have a very small effect on relative values. The values of $E/\sigma$ relative to mix D, found in this way, were averaged over the spectrum of x-rays generated by the 8 Mev linear accelerator of the Medical Research Council. The result is given in the second row of figures in the table.

In the third row an estimated correction is applied to allow for the wall of the chamber itself. This wall is about 0.5 mm thick, and provides a proportion of the ionization independently of the phantom material. When the chamber is exposed naked to the x-ray beam, the ionization is about 30% of that in the phantom. Evidently roughly 70% of the ionization arises from the phantom material, and the calculated relative ionization has been reduced in this proportion.

The calculated figures differ from the measured values by less than 1%, except in the case of water where the discrepancy is rather larger. The agreement is probably reasonable when allowance is made for experimental errors (a few parts per thousand), for uncertainties in the fundamental data given in the N.B.S. publications, and in particular for the approximate method of estimating the mean energy of the secondary electrons, which neglects the contribution from delta rays. Also, the measurements in water required the use of an impermeable rubber cover which may have affected the measured ionization.

The cause of these variations between different phantom materials is that the phantom has an additional function to perform when used in this way with megavoltage radiation, namely to provide part of the chamber wall. The usual criteria in selecting phantom materials are that they should have the same number of electrons per unit volume and the same 'effective atomic number' as tissue (or water). In this case the distribution of x-radiation is the same in the phantom as it is in tissue. But the ratio of $E/\sigma$ is not necessarily the same. In particular, varying proportions of hydrogen in ‘tissue equivalent’ phantoms give rise to variations in stopping power and hence of observed ionization.

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REFERENCES
HEAT OF REACTION BETWEEN FERROUS AMMONIUM SULPHATE AND HYDROGEN PEROXIDE IN AQUEOUS SOLUTION

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Received 3rd June, 1960

An isothermal microcalorimeter is used to measure the heat of reaction between ferrous ions and hydrogen peroxide in aqueous solution. The result is

$$2\text{Fe}^{2+} + \text{H}_2\text{O}_2 + 2\text{H}^+ \rightarrow 2\text{Fe}^{3+} + 2\text{H}_2\text{O} + 71.3 \pm 2.5 \text{ kcal/mole.}$$

This measurement throws light on a discrepancy between two values of the standard heat of formation of ferric sulphate in aqueous solution, given in National Bureau of Standards circ. 500.

In connection with a calorimetric method for the dosimetry of megavoltage X-rays, it was necessary to estimate the heat change in the solution of the Fricke dosimeter due to the radiochemical reactions. These reactions are well understood quantitatively \(^1,2,3\) so that it should be possible to estimate the heat of the reactions from standard heats of formation. However, two different heats of formation of ferric sulphate in aqueous solution are given by the National Bureau of Standards, circ. 500.\(^4\) Examples of values are \(\text{Fe}_2(\text{SO}_4)_3\) in 3000 moles \(\text{H}_2\text{O}\), 653.6 kcal/mole; 2 \(\text{Fe}^{3+}\) (aq), 22.8; and 3 \(\text{SO}_4^{2-}\) (aq), 650.7 making 673.5 kcal/mole for the ionized condition. Most of the heat evolved in the reactions of interest arises from the oxidation of ferrous sulphate by hydrogen peroxide: the N.B.S. data applied to this reaction in dilute solution lead to the following discordant values:

1. \(2\text{Fe}^{2+}(\text{aq}) + \text{H}_2\text{O}_2(\text{aq}) + 2\text{H}^+(\text{aq}) \rightarrow 2\text{Fe}^{3+}(\text{aq}) + 2\text{H}_2\text{O}(\text{liq}) + 72 \text{ kcal/mole H}_2\text{O}_2.\)

2. \(2\text{FeSO}_4(\text{aq}) + \text{H}_2\text{O}_2(\text{aq}) + \text{H}_2\text{SO}_4(\text{aq}) \rightarrow \text{Fe}_2(\text{SO}_4)_3(\text{aq}) + 2\text{H}_2\text{O}(\text{liq}) + 56 \text{ kcal/mole H}_2\text{O}_2.\)

The difference in the heat of reaction is so large that it was decided to measure it experimentally.

In this institution, the Fricke dosimeter is normally used in the form of \(10^{-3}\) M ferrous ammonium sulphate in 0.185 N sulphuric acid, and the heat of oxidation of this by 0.01 N \(\text{H}_2\text{O}_2\) has been measured. A measurement was also made using 0.8 N acid. At these concentrations of acid the heat of reaction (2) is 61 kcal/mole.

EXPERIMENTAL

The reaction took place in a 150 ml beaker containing about 100 ml of the ferrous solution. Samples of \(\text{H}_2\text{O}_2\) or water, having volumes in the range 0.5-1.1 ml, were run into the delivery tube (see fig. 1). After an interval of time for temperature-equilibration, the sample was transferred to the beaker by means of an air-filled syringe. The solution in the beaker was stirred by a glass-enclosed magnetic stirrer. Tests with a coloured dye indicated...
that mixing was complete in a few seconds. The temperature rise was measured by a glass-
enclosed thermistor (STC type F). Glass was therefore the only material in contact with
the solutions, which were prepared with the purity needed for use in the Fricke dosimeter.
Distilled water was redistilled twice from an all-glass apparatus, once from alkaline and
once from acid permanganate. The reagents used were A.R. quality.

The reaction vessel was contained in a Dewar flask which was itself surrounded by 7 cm
of powdered cork. This apparatus, which forms an isothermal microcalorimeter, was used
in an interior room with no windows, in which temperature variations were small.

Each sample of H$_2$O$_2$ oxidized about 10% of the ferrous ion and caused a temperature
rise of about 3 x 10$^{-3}$ °C. Samples of water were also used, in order to measure the heat of
dilution of the acid and in this case the temperature rise was about 4 x 10$^{-4}$ °C. These
temperature changes could be measured by means of a thermistor bridge network (see fig. 2).
A Wheatstone bridge containing two 100 K.Ω resistors and a matched pair of thermistors
each about 80 K.Ω at 25°C, was excited at 20 c/sec, the out-of-balance signal being fed to the
grids of a double triode type E88CC. The amplified signal was synchronously rectified by
a Carpenter-type polarized relay (Telephone Manufacturing Company) and displayed on a
recording potentiometer. The power dissipated in the thermistor was about 5µW and the
r.m.s. noise level corresponded to a temperature change of 10$^{-5}$ °C. A pair of thermistors
was used in order to mitigate the effects of fluctuations of the exciting voltage and of the
ambient temperature. The second thermistor was dipping into mercury in a small vessel
placed by the side of, but thermally insulated from, the reaction vessel.

During experimental work the trace of the recording potentiometer was calibrated in
terms of a change in the resistance r (see fig. 2) and this was converted into a change of
temperature by a calibration of the thermistor against a mercury-in-glass thermometer.
The sensitivity was found to be 4.50 K.Ω/deg. The effective heat capacity of the solid parts
of the calorimeter was measured by inserting an electric heating coil into the solution and
it was found to be 10.2 cal/deg. The calculated value was 9.6 cal/deg. With 100 ml of
solution this difference is only $\frac{1}{4}$ % of the total heat capacity.
RESULTS

Three separate solutions of hydrogen peroxide and of ferrous ammonium sulphate were made up, two of the latter in 0·185 N sulphuric and one in 0·8 N acid. In each case, 5 samples of H$_2$O$_2$ were added successively to the ferrous solution. The 3 sets of 5 measurements yielded the mean results given in Table 1. An experimentally determined correction has been applied for the heat of dilution of the acid. Allowance has been made for the specific heat of the solution (0·997 cal/ml deg. at 0·185 N acid, and 0·991 at 0·8 N).

<table>
<thead>
<tr>
<th>expt. no.</th>
<th>[acid] N</th>
<th>[H$_2$O$_2$] N</th>
<th>total</th>
<th>acid dilution correction</th>
<th>difference</th>
<th>heat of reaction kcal/mole</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0·185</td>
<td>0·0102</td>
<td>412</td>
<td>53</td>
<td>359</td>
<td>70·5</td>
</tr>
<tr>
<td>2</td>
<td>0·185</td>
<td>0·0104</td>
<td>429</td>
<td>53</td>
<td>376</td>
<td>72·4</td>
</tr>
<tr>
<td>3</td>
<td>0·8</td>
<td>0·0103</td>
<td>488</td>
<td>122</td>
<td>366</td>
<td>71·0</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>71·3</td>
</tr>
</tbody>
</table>

There was a tendency for the heat production per ml of H$_2$O$_2$ added to rise with the proportion of iron already oxidized, the last observation of each group of 5 being respectively 3 %, 6 % and 2 % greater than the first. This was not observed during measurements of the heat of dilution of the acid. It was found by Barb et al.\textsuperscript{5} that the presence of ferric ion can modify the reaction between ferrous ion and hydrogen peroxide. It seems unlikely that this would affect the results presented here, since the amount of ferric ion produced was checked spectrophotometrically at the end of each set of measurements, and was found to agree with the expected quantity to within 1 %. Nevertheless, it may be of value to consider separately the results of the first measurement of each group, in which there was no ferric ion present initially. These give the following values: 69·5, 69·3, 70·8 kcal/mole, with a mean of 69·9. This suggests a possible systematic error of 2 % in the mean value given in the table. Allowing for other possible systematic errors (1 % in heat capacity, 1 % in the strength of H$_2$O$_2$), the heat of reaction is 71·3 ±2·5 kcal/mole of H$_2$O$_2$.

The measurements of the heat of dilution of sulphuric acid can be compared with figures derived from N.B.S. circ. 500\textsuperscript{4} to give a check of the accuracy. This is done in Table 2, which gives the heat of dilution of a large volume of acid per mole of water added.

<table>
<thead>
<tr>
<th>[acid], N</th>
<th>expt. result</th>
<th>N.B.S. circ. 500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0·185</td>
<td>0·95±0·03</td>
<td>1·00</td>
</tr>
<tr>
<td>0·8</td>
<td>2·20±0·05</td>
<td>2·28</td>
</tr>
</tbody>
</table>

DISCUSSION

The heat of this reaction was found by Evans, Baxendale and Uri\textsuperscript{6} to be 65·5±2 kcal/mole, which is significantly different from the figure reported here. However, the conditions of measurement were not identical. Evans, Baxendale and Uri used 1·4 M FeSO$_4$ in 0·01 N HClO$_4$, which was mixed with H$_2$O$_2$ in a larger volume of N HClO$_4$, while in this experiment 10$^{-3}$ M ferrous ammonium sulphate in 0·18 N and 0·8 N H$_2$SO$_4$ was used. The present measurement agrees closely with that derived from heats of formation of aqueous ions given in N.B.S. circ. 500.\textsuperscript{4} The heat of formation of Fe$_2$(SO$_4$)$_3$ (aq) leads to a heat of reaction
HEAT OF REACTION BETWEEN Fe$^{2+}$ AND H$_2$O$_2$

which disagrees both with this measurement and with that of Evans, Baxendale and Uri. Further, the references given for the heat of formation of Fe$_2$(SO$_4$)$_3$ (aq) in N.B.S. circ. 500 are old (1873, 1882, and 1924) and its inclusion in the tables would appear to have little value.

I would like to thank Dr. M. E. Ebert of the M.R.C. Radiopathological Research Unit for his help and interest in the measurements.

2 Allen and Rothschild, Radiation Research, 1957, 7, 591.
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The

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MATERNAL AND FOETAL RADIATION DOSAGE DURING OBSTETRIC RADIOGRAPHIC EXAMINATIONS


Departments of Radiodiagnosis and Physics, Hammersmith Hospital, London, W.12
(Received January, 1957)

The increasing production of ionizing radiations in the world constitutes a long-term genetic hazard. In this country diagnostic radiology is the most important artificial source of genetically significant radiation (Medical Research Council, 1956), and obstetric examinations, which contribute about 29 per cent of the total dose, are particularly important from this point of view (Osborn and Smith, 1956). Also, there is some evidence (Stewart, Webb, Giles and Hewitt, 1956) that obstetric radiology may initiate malignant changes in the foetus, increasing the incidence of leukaemia and other malignant conditions in subsequent childhood.

There are few published measurements of the dosage delivered to the foetus and to the maternal ovaries during diagnostic examinations. Osborn (1951) and Stanford (1951) have estimated the dose to the foetal gonads in pelvimetry. Stanford and Vance (1955, 1956) have also made an extensive study of the dose to the gonads during many other radiographic procedures.

The object of this paper is to provide comprehensive measurements of the radiation received by the mother and foetus during certain obstetric radiographic procedures using a high kilovoltage technique (100 to 120 kVp), to compare these results with those obtained using the conventional low kilovoltage technique (80 to 85 kVp), and to suggest means for reducing the radiation as far as possible.

METHOD

In order to study the distribution of dosage in high kilovoltage obstetric radiography, it was decided to construct models having the shape of the maternal abdomen, on which comprehensive depth dose measurements could be made. Two patients at term were chosen as representative of the extreme variation in size likely to be encountered. One was large (47 in. girth, 15 in. bitrochanteric diameter) on whom one would expect to use maximum radiographic factors, and the other small (37 in. girth, 12.5 in. bitrochanteric diameter, height, 4 ft. 9 in.) who represented one type of patient on whom pelvimetry is commonly carried out. These patients kindly consented to help in the experiment by allowing us to make plaster casts of their abdomens. The skin markings of the xiphisternum, umbilicus, symphysis pubis, iliac crests and lumbosacral junctions were marked on the plasters to aid subsequent orientation. The long axis of the uterus, the true conjugate, and the level of the iliac crests were then indicated within the models by wires conjoining known surface landmarks.

Fig. 1. The smaller plaster cast set up for a radiographic exposure of a lateral pelvimetry.
Maternal and Foetal Radiation Dosage during Obstetric Radiographic Examinations

plaster was by no means uniform in thickness and an average figure of 10 per cent has been used in deriving the figures in Table I.

The radiographs in the postero-anterior view of an obstetric abdomen were taken with the patient compressed by an amount up to 10 cm with a compression band, and it was impossible to simulate this condition with the plaster casts. For this view we used only the smaller plaster, and made some allowance for compression by placing the ionization chambers 2.5 cm further back; the figures for this 50 per cent, but in certain cases where a point was inside the beam for the small cast and outside for the large one the difference was greater. The doses and the radiographic factors given in the table are for the larger cast.

Points B to E lie along the axis of the uterus (Fig. 2). Points G to J lie anteriorly and laterally (Fig. 3) and receive relatively large doses in the lateral abdominal view. In a lateral pelvimetry these points lie at the edge of the field, and the doses would be very susceptible to small changes in field position.

TABLE I

| RED SEAL FILM. 1 MM AL FILTER ADDED. HIGH KILOVOLTAGE SCREENS |
|---------------|-----------------|-----------------|-----------------|-----------------|
| Pelvimetry   | Obstetric abdomen |                |                |                |
|              | Lateral | Inlet | Outlet | Total | Lateral | P.A. |                |                |
| kVp          | 120     | 120   | 108    | 111   | 99      |      |                |                |
| mAs          | 75      | 130   | 75     | 50    | 50      |      |                |                |
| F.P.D.       | 36 in.  | 36 in.| 40 in. | 40 in.| 40 in.  |      |                |                |
| F.S.D.       | 49 cm   | 48 cm | 69 cm  | 63 cm | 71 cm   |      |                |                |
| Cone area at 30 cm F.D. | 10 x 10 cm | 10 cm dia. | 10 cm dia. | 13.5 cm dia. | 13.5 cm dia. |      |                |                |

Reference point:

A Xiphisternum  0-01  11.5  0  11.5  0.02  0.01  0.03
B 2-5 cm deep to A  0-02  6.3  0-01  6.3  0.1  0.07  0.17
C 9 cm deep to A   0-05  2.6  0-02  2.7  0.2  0.2  0.4
D Midway between iliac crests  0-4  0.3  0-2  0.6  0-1  0.15  0.25
E Pelvic inlet      0-4  0.04  0-2  0.6  0-1  0.15  0.25
F Maternal ovary    0-1  0.5  0-03  0.6  1.0  0.2  1.2
G 5 cm deep to A       0-2  0-04  0-9  0-9  0-9  0-9  0-9
H 8 cm deep to A       0-3  0-1  0-4  0-4  0-4  0-4  0-4
I 9 cm deep to A       0-3  0-02  1.2  1.2  1.2  1.2  1.2
J 10 cm deep to A      0-2  0-02  0-25  0-25  0-25  0-25  0-25
Skin entry           5.8  11.5  2.6  2-4  1.3  2.4  3.3

Foetal gonads:

Vertex 5 cm deep  0-06  4.6  0-01  4.7  0-15  0.12  0.27
Breech presentation 8 cm deep  0-14  2.8  0-02  3.0  0-18  0.17  0.35
Breech presentation 8 cm deep  0-41  0.04  0-20  0-6  0-13  0.15  0.28
Average            0-1  2.8  0-02  2-9  0-2  0.15  0.35

Note: The positions of the reference points are shown in Figs. 2 and 3.

Results

Doses at selected points

Table I shows the doses measured at various points within the plaster casts. The doses received in the two sizes of cast were not as different as might be expected since variation in the size of the patients was allowed for by adjusting the kilovoltage and not the mAs. The differences were usually less than view are less reliable than the others. When estimating the average dose to the foetus (see below), the figure for this view was derived from measurements of the doses at the entrance and exit points, measured on patients.

The maternal ovaries near term are carried out of the pelvis by the expanding uterus. We have taken them as lying in the mid coronal plane 7 cm above the level of the iliac crests and 7 cm deep to the skin in the lateral direction (8 cm deep for our large plaster). In this position the ovaries lie outside the beam in a lateral pelvimetry. The doses to the maternal ovaries given in Table I refer, in the case of lateral views, to that ovary which is closer to the X-ray tube.

The dose received by the foetal gonads is of special interest. In a vertex presentation the gonads usually lie at a depth of between 5 and 8 cm from the surface and the doses received at these points are 287

The averaging process is necessarily extremely rough. We have assumed the foetus to be an ellipsoid of revolution, 23 cm long and 16.3 cm in diameter. (This gives a weight of 7 lb for unit density). The long axis is taken to lie along the central ray for the inlet view and the ellipsoid extends from 6 to 29 cm deep to the surface along this line. Points C, D and E, in Table I lie on this axis.

FACTORS INFLUENCING DOSES IN RADIOGRAPHY

(a) Film and screen

Our figures refer to fresh Ilford Red Seal film between high kilovoltage screens. We have measured the relative speed of Red Seal and Standard film under conditions corresponding to pelvimetry, and the use of Standard film would entail nearly doubling the exposure, and hence nearly doubling the dose levels. Also, we have found that high kilovoltage screens are about twice as fast as standard tungstate screens, both at 84 and 120 kVp.

These measurements together with those described in Section (e) below were made with the cassette below a Bucky and a phantom of tissue equivalent material 30 cm thick.

(b) Processing

We have used Kodak DX 80 developer, under the standard conditions recommended by the makers.
Maternal and Foetal Radiation Dosage during Obstetric Radiographic Examinations

(c) Grid
We have used a Lucidex grid with grid ratio 10 : 1 and lead slat to interspace in the ratio 4 : 15.

(d) Focal-film distance
We have used 36 in. for some views. An increase to 40 in. would reduce the dose at a depth of 5 cm in the inlet view by about 15 per cent for the same irradiated area on the film. The Bucky is focused for 36 to 40 in. and an increase beyond 40 in. would require additional radiation to overcome the reduced transparency of the Bucky.

(e) Kilovoltage and filtration
We have compared the doses needed for a given blackening of the film at 84 and 120 kVp with 1 mm of aluminium added filter and at 120 kVp with various amounts of additional filtration. The results are shown in Fig. 4. The dose needed by the film to give a density of unity was roughly the same in every case (1 mr). It can be seen that the use of a high kilovoltage and filtration causes a very marked reduction in the dose to the skin, but that the improvement is steadily reduced on moving to a depth in the phantom, becoming of little value at depths of 20 cm and below. However, the improvement is most marked where the doses are largest. For example, from 5 to 8 cm deep, where the foetal gonads usually lie in the inlet view, the dose at 120 kVp is about 60 per cent of that delivered at 84 kVp, while the use of a filter of 0.25 mm Cu reduces the dose to 45 per cent. We have therefore tried using a filter of 0.25 mm Cu and we found that, while in a lateral pelvimetry this filter caused a hardly discernible loss of contrast, for abdominal views the loss of contrast reduced the diagnostic value of the films.

This comparison of 84 and 120 kVp is perhaps unfair, because at the lower kilovoltage a lower ratio grid could be used and this would make the dose levels at 84 kV less unfavourable. However, the work of Nemet, Cox and Hills (1953) shows that if, for example, one changed from a 10 : 1 to an 8 : 1 grid, the reduction of exposure would be small.

DISCUSSION
If radiography in utero initiates malignant change as suggested by Stewart, Webb, Giles and Hewitt (1956), the average dose throughout the foetus seems the best way of estimating the risk involved in the various projections used. The inlet view contributes two-thirds of the total dose delivered in a three-film pelvimetry (Table II). Moreover, this projection contributes by far the greatest dose to the foetal gonads (Table I). Although this view gives the best idea of the shape of the pelvic inlet it is not essential for the purpose of pelvic measurements and can usually be omitted.

The lateral view also delivers a large skin dose, but the irradiated field is small and includes only part of the foetus. It is particularly important in this view to use as small a cone as possible.

Our doses at comparable positions are lower than those of Stanford (1951). The figure of the dose to the foetal gonads in pelvimetry given in the Medical Research Council publication entitled The Hazards to Man of Nuclear and Allied Radiations is, however, slightly smaller than ours (2.68 r). This figure is based on the work of Stanford and the discrepancy appears to be due to the foetal gonads having been taken as lying at too great a depth in the inlet view.

Our measurement of the skin dose in the inlet view is similar to that of Kemp (1954), who found
values of 7 to 10 r for 120 kVp radiation with 3 mm Al filtration. We agree with Kemp (1954) that with higher voltage radiography the radiographs show lower contrast than those taken with the more conventional low kilovoltage techniques. However, the outlines of the important bony and soft tissue structures are shown satisfactorily.

It may be of interest to compare the dose delivered to the foetus during placental localisation by radiographic and radioactive sodium methods. In this hospital 100 µc of sodium 24 are used. Assuming uniform distribution of the sodium, this delivers an average dose to the foetus of about 0.2 r (Marinelli, Quimby and Hine, 1948). It is interesting to note that this is about the same as one radiograph of the obstetric abdomen by our technique. In fact two or more films may be necessary, but a comparison of the value of the two methods is beyond the scope of this paper.

CONCLUSIONS AND RECOMMENDATIONS

1. We find that the use of a high kilovoltage technique (100 to 120 kVp) results in lower maternal and foetal doses than the more usual low kilovoltage techniques (80 to 85 kVp), other factors being kept constant. The skin dose is reduced to one half and the improvement persists to all depths.

2. High kilovoltage screens and fast films should be used. We find that in each case the doses are reduced to half of those needed when using the standard article. Ilford Red Seal film has proved satisfactory.

3. The inlet projection delivers by far the largest doses and should be used only when considered absolutely essential.

4. It is essential that repeat exposures be kept to a minimum and that the smallest practicable cone should be used. For this reason we suggest that obstetric radiography should be carried out only by experienced radiographers.

5. In order to keep a check on the radiation delivered to individual patients, a record should be kept of all exposures made as well as all films taken.

SUMMARY

Tissue equivalent phantoms have been used to estimate the dose to various parts of the foetus and to the maternal ovaries during obstetric radiography at 100 to 120 kVp. These phantoms were made by taking plaster casts of pregnant women at term. An estimate has been made, for each projection, of the dose delivered to the foetal gonads in the average case. An estimate has also been made of the value of the dose averaged over the whole foetus, for each projection. The inlet projection is found to give rise to by far the highest radiation levels. A short investigation was made of the various factors which influence the doses delivered in radiography and some recommendations are given on methods of keeping the doses to a minimum.

REFERENCES

INTEGRAL DOSES AT 200 kV AND 8 MeV*

E. Nataaddidjaja, B.Sc., G. R. Newbery, B.Sc., F.Inst.P., and R. Opie,
M.I.R. (Australia)

Radiotherapeutic Research Unit of the Medical Research Council, Hammersmith Hospital, London, W.12

WHEN X-ray treatments were begun on the 8 MeV linear accelerator of the Medical Research Council's Radiotherapeutic Research Unit at Hammersmith Hospital, it was thought that a comparison of the integral doses delivered during treatment at 8 MeV and at 200 kV might help in understanding the response of patients to treatment at these two qualities. Calculations of integral doses at the two qualities have therefore been made, and checked by measurements using the Celluloid Man. Various measurements with the Celluloid Man have been reported by Boag (1945), Wood and Boag (1950) and Grimmett (1942), but a comprehensive account of its construction and method of use has not previously been given.

Little success in correlating clinical reactions with integral dose has been reported in the literature, but one reason for this might be the difficulty of obtaining a reliable estimate of integral dose. For example, calculations at 200 kV based on isodose charts drawn to 10 per cent can be very seriously in error (Johns, 1953; Mayneord, 1940). This is the first time (to the authors' knowledge) that methods of calculation have been checked by direct measurement.

Another possible reason for this lack of success is that integral dose may not be the best available statistic, owing to variation in the size of individual patients. If two patients, one very large and the other very small, are treated with the same field area, a greater fraction of the small patient's body is irradiated. For equal applied doses one might therefore expect that the small patient would experience the more severe reaction. But he receives a smaller integral dose than the large patient, as his thickness is less. On the other hand, the small patient receives the larger average dose (integral dose divided by mass). Perhaps average dose is a more significant quantity when allowing for variation in the size of patients. For this reason, we have quoted integral doses in megagram rads and megagram röntgens. One megagram rad is 10 joules by definition, but values given in megagram rads are easier to convert to average doses.

* A paper read at the Annual Congress of the British Institute of Radiology on November 29, 1957.

Calculations at 8 MeV

At 8 MeV calculations have been made for square fields of various sizes, using isodose charts based on measurements in water along the axis and diagonal of the fields. Specimens of these charts have been published (Newbery and Bewley, 1955).

For the main beam (down to 5 per cent) the three-dimensional dose distribution was divided into a series of sections lying perpendicular to the beam axis; the average dose for each section was found graphically and multiplied by the distance between adjacent sections.

Outside the 5 per cent contour there is still an appreciable amount of radiation; this has been described by Newbery and Bewley (1955). Although the intensity at a given distance outside the field is greater for large fields, the proportional contribution to the integral dose is more important for small fields. We have made measurements of this radiation, and we found that the isodose curves gradually change from squares to circles. We have made a rough calculation of the integral dose outside the 5 per cent level by assuming that the isodose surfaces are cylindrical, the radii being the average of measurements taken along the axes and diagonals of the square fields, at a depth of 10 cm.

It is difficult to decide how large a volume outside the main beam should be included. We have included the radiation in a cylinder 40 cm in diameter, as a compromise between the length and breadth of the trunk, although this is, of course far too large for fields on the head and neck. The dose outside the 5 per cent contour makes up 31 per cent of the total integral dose for a field 4×4 cm, 12 per cent for 10×10 cm, and 3 per cent for 20×20 cm, in each case for a parallel-sided slab of water 20 cm thick. Fig. 1 shows the calculated values of integral dose as a function of thickness and field area.

Calculations at 200 kV

At 200 kV it is not possible to use isodose charts for accurate calculations because of the large contribution from volumes where the percentage depth dose is small and not recorded on the isodose charts. Several workers have tried to overcome this difficulty by using the method known as “saturated
scatter" (Happey, 1941; Loeffler, 1956). Consider a beam of X rays incident on a water phantom, the beam being uniform and so wide that a further increase in width causes no addition to the depth doses on the central axis. The integral dose due to a pencil of rays which strikes a small area on the surface of the phantom at the centre of the beam can be calculated by integrating the dose measured throughout the volume enclosed by this pencil, because in a very large field the energy lost by quanta scattered out of the volume is exactly made up by energy scattered in. For a small isolated field this pencil of rays contributes the same integral dose, if the volume of integration extends far enough in a lateral direction. One difficulty of this method lies in the enormous field sizes needed to give saturation at a depth. We have used the method of Meredith and Neary (1944), in which extrapolation to an infinite field depends on an empirical function. This method has the additional advantage that the integration can be limited to any desired volume, so that the radiation scattered laterally out of the patient need not be included. The method is not strictly correct for an isolated body, as there is no returning scatter from the absent material which is assumed to lie around it. However, the error is unlikely to be large except for grazing fields. The latest values of the constants (Horsley and Aspin, 1956) have been used in the calculations.

The most convenient way of applying Meredith and Neary's method is to calculate the integral dose received by truncated confocal cones, as indicated in Fig. 2. Fig. 3* shows the result, plotted against the thickness of the conical frustum, for a half-value layer of 2 mm of Cu and 50 cm F.S.D. It can be seen that only a small proportion of the energy is scattered beyond a 30 cm cone. On the other hand the integral dose is still increasing steadily with thickness even at a depth of 30 cm. The integral dose is given in gram-röntgens per cm² of the field on the surface, per röntgen delivered in air at the surface. The calculations actually yield röntgen-c.c., and a factor of 1.06 (whose derivation is explained in Appendix B) has been used to convert to gram-röntgens. Air doses rather than skin doses are used because the one diagram then serves (approximately) for all field sizes. Actually the integral dose per cm² falls with increasing field size; as the diameter of the field approaches that of the cone in which the integral dose is being estimated, an increasing proportion of the scatter escapes laterally. However, the effect of field size is smaller than might be supposed. Fig. 3 is drawn for a circular field 10 cm in diameter, as a compromise between large and small fields. The integral dose per cm² delivered within a 15 cm diameter cone is 4 per cent greater for a 5 cm diameter field and 7 per cent less for a field 13.8 cm in diameter (15 x 15); for larger cones the effect of varying the field-size is even less important.

It is of interest to consider the distribution of the energy in a beam of X rays that is used to irradiate the trunk of an average patient. As an approximation, calculations have been made for a truncated cone 23 cm thick and 25 cm in diameter at the small end. Then, for a field 10 cm in diameter, we have

* Enlarged copies of Fig. 3 may be obtained from the Hospital Physicists' Association Diagrams and Data Scheme.
Integral doses for radiation of H.V.L. 2 mm of Cu calculated by Meredith and Neary’s method for confocal cones of various sizes.

The incident energy was calculated for the spectrum given by Johns (1953) for a half-value layer of 1.8 mm of Cu. The calculation of the back-scattered energy is explained in Appendix A. The balance of 2.5 per cent which is unaccounted for is gratifyingly small.

The Celluloid Man

We have attempted to check these calculations at both qualities of radiation by using the Celluloid Man. This model of the human body is intended to have the same average properties as tissue, and contains a large number of ionization chambers connected in parallel so that the total ionization current when the model is irradiated is proportional to the integral dose delivered.

The model is made of cellulose acetate plates 6 mm thick, which are kept apart at a separation of 2 mm by annular washers of the same material. These washers also serve to define the volume of the air spaces in the plane of the plates. The washers are about 1 cm wide, except that in the latest reconstruction of the head, in 1954, the washers were made 8 mm wide. All the plates would lie horizontally if the model were stood up.

The surfaces of the plates are graphited, and the plates are connected together alternately. One set constitutes the “H.T. electrodes” and the other the “collecting electrodes”, the latter set being joined together internally. The part of the surface of each “collecting electrode” which is in contact with the spacer is insulated from the remainder by a groove and forms a guard ring. A sensitive galvanometer measures the ionization current. The density of cellulose acetate is 1.3, giving an average density very near to unity, so that the distribution of X rays in the model is almost the same as it would be in a human body of the same size. The connections to different parts of the body are brought out separately to enable the contributions of the parts to the total integral dose to be measured.

The separate parts are: head, neck, trunk—two parts (left and right), two thighs and one leg with foot. There are no arms or hands. There is an orifice for inserting gynecological radium. The dimensions of the parts are given in Table I.

| TABLE I |
| DIMENSIONS OF THE CELLULOID MAN, INSIDE THE GUARD RING |

<table>
<thead>
<tr>
<th>Measurements</th>
<th>cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference in plane of occipito-frontal</td>
<td>54</td>
</tr>
<tr>
<td>diameter</td>
<td></td>
</tr>
<tr>
<td>Bitemporal diameter</td>
<td>13</td>
</tr>
<tr>
<td>Occipito-frontal diameter</td>
<td>17</td>
</tr>
<tr>
<td>Occipito-mentual diameter</td>
<td>24</td>
</tr>
<tr>
<td>Mid neck lateral diameter</td>
<td>10</td>
</tr>
<tr>
<td>Mid neck antero-posterior diameter</td>
<td>11</td>
</tr>
<tr>
<td>Mid sternal antero-posterior diameter</td>
<td>23</td>
</tr>
<tr>
<td>Mid sternal lateral diameter</td>
<td>34</td>
</tr>
<tr>
<td>Level of umbilicus, antero-posterior diameter</td>
<td>22</td>
</tr>
<tr>
<td>Level of umbilicus, lateral diameter</td>
<td>31</td>
</tr>
<tr>
<td>Level of symphysis pubis, antero-posterior</td>
<td>24</td>
</tr>
<tr>
<td>diameter</td>
<td></td>
</tr>
<tr>
<td>Level of symphysis pubis, lateral diameter</td>
<td>37</td>
</tr>
<tr>
<td>Length symphysis pubis—suprasternal notch</td>
<td>56</td>
</tr>
<tr>
<td>Mid thigh, circumference</td>
<td>49</td>
</tr>
<tr>
<td>Mid calf, circumference</td>
<td>31</td>
</tr>
<tr>
<td>Length of foot</td>
<td>22</td>
</tr>
</tbody>
</table>
Integral Doses at 200 kV and 8 MeV

Cellulose acetate is not really the most satisfactory material because it warps and decomposes. For example, when the model was dismantled in 1954 it was found that the plates had warped and shrunk by varying amounts, frequently shearing the plastic pins that hold the model together. Also a heavy concentration of acetic acid vapour was released. This means that the ratio of the volumes of cellulose acetate to air is not necessarily 6 to 2.

Even now sheets of cellulose acetate are not of uniform thickness. Three sheets and two pieces out of the batch used for a reconstruction in 1954 yielded a range of thickness from 5.70 to 6.45 mm, with a mean of 6.03 mm. One of the old sheets in the head was only 5.4 mm thick. The polished layer of graphite on each side adds on only about 0.004 mm. On the occasion of some measurements in 1955, the length of the anterior part of the trunk was found to be 58.2 cm. There are 71 plates in this distance, with an H.T. plate at each end. There were therefore 70 complete sections in 57.6 cm giving 8.23 mm per section. Taking the cellulose acetate plates as 6 mm thick, this gives the air spaces as 2.23 mm in thickness, or 11 per cent greater than the theoretical value. In the head there was 2.31 mm of air per section. These figures for the thickness of the air spaces are, of course, only average values.

The presence of acetic acid vapour should not directly affect the ionization current to an appreciable extent. The vapour pressure of acetic acid at 20°C is 11.6 mm of Hg. Taking the vapour density of acetic acid as double the density of air at the same pressure, the increase in ionization current to be expected is \( \frac{771.6}{760} - 1 \) or 1.5 per cent. Normally a polarising voltage of 30 V was used. This ensures a collection efficiency of at least 99.5 per cent.

To obtain unambiguous results from the model, two conditions should hold. The dose distribution in the model should be the same as in a water phantom of identical shape and size, and the ionization chambers of which the model is composed should be “air-walled”. If this were so, the integral dose delivered would be given by:

\[
X = 3 \times 10^3 \left( \frac{a+b}{a} \right) I \text{ röntgen c.c. per second at S.T.P.,}
\]

where \( I \) is the measured ionization current in amps, \( a \) is the thickness of the air spaces and \( b \) is the thickness of the cellulose acetate plates. To obtain the integral dose delivered to a water phantom of identical shape and size, the result should be multiplied by a factor to convert from röntgen c.c. to gm.r in water.

Comparison of measured and calculated values

Three field positions have been used for a comparison of measured and calculated integral doses. Volumes used for calculated values of integral dose: Cylinder at 8 MeV. Cone at 2 mm of Cu H.V.L.

In fact neither of these conditions is strictly true, although it seems that the first one is fulfilled to an adequate extent. This matter is discussed in Appendix B, where in addition there is an account of the connections that have to be applied to allow for the effects of the washers and guard rings, the laminated structure of the model and the atmospheric pressure and temperature.

Our measured integral doses at a half-value layer of 2 mm Cu for fields on the trunk are about 15 per cent less than those given by Boag (1945). This is mainly accounted for by the error in the standard free air chamber at the National Physical Laboratory; with Dr. Boag we have recently checked the calibration of one of the chambers which he had used, and we found that its sensitivity had increased by 10 per cent, a figure remarkably close to the average of dosemeters (Day, 1956). Our results are probably as close to those of Boag as could be expected, allowing for different techniques of measurement and for the fact that the Celluloid Man has been reconstructed in the interval.

Comparison of measured and calculated values

Three field positions have been used for a comparison of measured and calculated integral doses.

**Table II**

Geometrical approximations to the celluloid man

<table>
<thead>
<tr>
<th>Diameter ( d ) cm</th>
<th>Thickness, ( h ) cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H.V.L. = 2 mm of Cu</td>
</tr>
<tr>
<td>Chest</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Pelvis</td>
<td>{ 20–27 }</td>
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<td></td>
<td>{ 27–33 }</td>
</tr>
<tr>
<td>Head</td>
<td>18</td>
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</tbody>
</table>

Fig. 4.

Geometrical shapes used in the comparison of measured and calculated values of integral dose. Volumes used for calculated values of integral dose: Cylinder at 8 MeV. Cone at 2 mm of Cu H.V.L.
They are the positions for which graphs were given by Boag (1945), namely pelvis: antero-posterior, mid-line; chest: antero-posterior, mid-line; and on the side of the head, roughly over the ear. For comparison with measurements made with these fields, calculations have been made by choosing simple geometrical shapes as approximations to the shape of the model. For the sake of convenience, frusta of cones have been used at a H.V.L. of 2 mm of Cu, and cylinders at 8 MeV, the diameters being matched at the mid-point (Fig. 4 and Table II). The thickness at 8 MeV is 1 cm greater than at a half-value layer of 2 mm of Cu because of the different methods used to allow for the guard ring (see Appendix B). The pelvis of the model has a more or less elliptical cross-section and a stepped arrangement has been used as an approximation to this. These shapes were chosen to fit the transverse cross-sections of the model, and a small amount has been added to the calculated values to allow for the axial extension of the trunk (about 1 per cent for the chest, and up to 10 per cent for the pelvis at H.V.L. = 2 mm of Cu).

Figs 5, 6 and 7 compare the theoretical and measured values. The agreement is probably as good as can be expected considering all the approximations involved. At H.V.L. = 2 mm of Cu and for fields not larger than 150 cm², the difference is less than 7 per cent for all sites. This seems to confirm the validity of Meredith and Neary's method. Of course it would be possible to obtain perfect agreement by choosing a suitable volume for the calculations, but here the sole criterion was that the

Vol. XXXII, No. 373


Comparison of measured and calculated values for fields on the pelvis, chest and head. The line gives the calculated values, and the crosses represent measurements made with the Celluloid Man.

Fig. 8.

Integral doses at the two qualities for 1000 rads delivered at various depths. Measured with the Celluloid Man.
Integral Doses at 200 kV and 8 MeV

Comparison of integral doses delivered at the two qualities

We have used the Celluloid Man to make a direct comparison of the integral doses delivered at the two qualities. The measurements were all made during one day, using the same field sizes and positions in each case. The conditions were: (a) H.V.L. = 1.9 mm of Cu, using a Westinghouse Duocondex unit running at 200 kV with 2 mm of Cu + 1 mm of Al filter, at 50 cm F.S.D.; and (b) the 8 MeV linear accelerator with aluminium beam-flattening filter, at 100 cm F.S.D. Fig. 8 shows the result for a 10 × 15 cm field applied centrally antero-posterior to the pelvis. The integral dose in each case is given in megagram rads per 1000 rads delivered at various depths. A small correction has been applied to make the integral doses strictly comparable in spite of the different methods of allowing for the guard ring in the two cases. The antero-posterior thickness of the pelvis inside the guard rings is 21 cm. It will be seen that if equal doses are delivered to a point 2 cm deep in each case, the integral dose at 8 MeV is 1.25 times the integral dose at 200 kV. For equal doses at 6 cm deep the integral doses are equal. Similarly, for 10 cm deep, 200 kV delivers 1.37 times the integral dose, and for greater depths the improved depth dose at 8 MeV makes the two curves rapidly diverge.

The Celluloid Man is not very suitable for a comparison of treatment techniques that could be used with individual patients, because of the effect of body size. Instead, integral doses have been calculated by the methods already described; this would seem to be valid as the Celluloid Man has checked the correctness of the calculations. Treatments of the thoracic region have not been included because the low average density of lung tissue makes the calculations (and also measurements with the Celluloid Man) quite unrealistic.

Table III gives the results of the calculations for five patients. All these were actually treated at 8 MeV. A treatment plan has also been made for 240 kV, designed to treat the same tumour area as at 8 MeV. In both cases the field arrangements are coplanar; the actual arrangements for one patient are shown in Fig. 9. Columns 6 and 7 show the integral doses in megagram rads for a dose of 1000 rads to the centre of the tumour. It will be seen that the integral doses delivered at a H.V.L. of 2 mm of Cu are not very much larger than those at 8 MeV. There are various reasons for this:

1. Compression is possible at H.V.L. of 2 mm of Cu. Some allowance has been made for this, as shown in Fig. 9.

2. At a H.V.L. of 2 mm of Cu the isodose lines are curved, so that the dose delivered on the central plane is greater than on any other plane. To deliver

\[ \text{H.V.L. = 2 mm of Cu} \]

\[ \text{8 MeV} \]

\[ \text{H.V.L. = 2 mm of Cu} \]

\[ 8 \text{ MeV} \]

\[ \text{I.D. megagram rads for 1000 rads M.T.D.} \]

<table>
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<tr>
<th>Patient</th>
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<th>Area of body section cm²</th>
<th>Field arrangements</th>
<th>I.D. megagram rads for 1000 rads M.T.D.</th>
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</thead>
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</tr>
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<td>Bladder</td>
<td>550</td>
<td>4 at 10 × 8</td>
<td>5 at 10 × 8</td>
</tr>
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<td>Bladder</td>
<td>880</td>
<td>4 at 10 × 8</td>
<td>5 at 10 × 9</td>
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<tr>
<td>IL 38</td>
<td>Cervix stage IV</td>
<td>535</td>
<td>4 at 10 × 10</td>
<td>5 at 10 × 10</td>
</tr>
<tr>
<td>EL 26</td>
<td>Antrum</td>
<td>175</td>
<td>1 at 6 × 5</td>
<td>3 at 6 × 5</td>
</tr>
</tbody>
</table>

Fig. 9.

Field arrangements for patient FL329, showing positions of fields used at 8 MeV and hypothetical arrangement for radiation of H.V.L. = 2 mm of Cu.
the same mean dose, averaged throughout the tumour, the figures for this radiation would have to be increased by up to 10 per cent for a 10 cm field.

3. Different field arrangements are used. At a H.V.L. of 2 mm of Cu the low depth doses require the fields to be applied as close as possible to the tumour. At 8 MeV this limitation is much less severe, and the fields can be applied further away if this gives a more uniform dose distribution. The last column of Table III shows the integral doses that would result from applying the 2 mm Cu fields in the positions actually used at 8 MeV; the integral doses are considerably increased for the larger patients.

**CONCLUSION**

Calculated values of integral doses delivered at 200 kV and 8 MeV have been found to agree with measured values using the Celluloid Man. At 200 kV the calculated values were obtained by Meredith and Neary's method, and at 8 MeV by direct computation from measured isodose charts. Measurements with the Celluloid Man show that, for equal tumour doses delivered by a pelvic field, the integral dose at 8 MeV is less than that at 200 kV provided the tumour is at a depth greater than 6 cm, and for tumours at more than 12 cm deep the difference between the two qualities of radiation is substantial. However, in multiple-field treatments of deep-seated lesions this advantage may be largely lost owing to the different field arrangements used.

**ACKNOWLEDGMENT**

We would like to thank Dr. J. W. Boag for his most helpful advice on the interpretation of measurements made with the Celluloid Man. Without this advice this paper would hardly have been possible.

**SUMMARY**

Calculated values of integral doses delivered during radiotherapy at 8 MeV and with radiation of H.V.L. = 2 mm of Cu are presented. These values have been checked experimentally. Meredith and Neary's method is found to give reliable values of integral dose at H.V.L. = 2 mm of Cu. The experimental measurements were made with a celluloid model of the human body, the model being composed entirely of ionization chambers. A description of the model is given, together with an analysis of the derivation of integral doses from measured ionization currents. The integral doses delivered during typical treatments at the two qualities are compared. It is found that in practice integral doses are not always greatly reduced at 8 MeV, owing to the differing field arrangements used.

**REFERENCES**


**APPENDIX A**

Energy back-scattered for radiation of H.V.L. = 2 mm of Cu $\lambda_{20}$ for incident radiation = 0·118 A.U. $\lambda_{20}$ for backscattered radiation = 0·2 A.U. roughly (Greening and Wilson, 1951).

The saturation back-scatter factor is about 1·45 (see table of the constant "M" given by Horsley and Aspin, 1956).

Using data from Hine and Brownell (1956), the energy flux per röntgen for the back-scattered radiation is 0·85 of that for the incident radiation. There is also a geometrical factor. The incident rays are perpendicular to the surface, while the back-scattered ones are not. Assuming the back-scattered radiation to be isotropic, and with unit intensity per unit solid angle, the intensity of the radiation at an angle $\theta$ to the normal to the surface is $2\pi \sin \theta \, d\theta$. At this angle, unit area of cross-section of the beam of X rays is spread over $\frac{1}{\cos \theta}$ cm$^2$ of the surface.

Therefore, the energy escaping through each cm$^2$ of the surface is

$$\int_{0}^{\pi/2} 2\pi \sin \theta \, \cos \theta \, d\theta = \pi$$

On the other hand the intensity at the surface is given by

$$\int_{0}^{\pi/2} 2\pi \sin \theta \, d\theta = 2\pi$$

as an ionization chamber should have a uniform response at all angles. The estimated intensity must therefore be divided by two to give the energy flux across the surface. The proportion of the energy back-scattered is then $\frac{1}{4} \times 0·45 \times 0·85$, or 19 per cent.

The main source of inaccuracy in this calculation probably lies in the use of the figure 0·2 A.U. to specify the quality of the back-scattered radiation; in this region the energy-flux per röntgen is varying rather quickly with wavelength.

**APPENDIX B**

On the derivation of the integral dose from measured ionization currents in the Celluloid Man

The following equation is given in the text:

$$X = 3 \times 10^6 \left( \frac{a+b}{a} \right) I \text{ röntgen c.c./second at STP}.$$ (1)

where $I$ is the measured ionization current in amperes, $a$ is the thickness of the air spaces and $b$ is the thickness of the cellulose acetate plates.
Integral Doses at 200 kV and 8 MeV

For this equation to be strictly true, two conditions must hold, viz. (1) the dose distribution in the model is the same as in a water phantom of identical shape and size, and (2) the ionization chambers of which the model is composed are "air-walled". In fact neither of these conditions is strictly fulfilled. Boag (private communication) investigated the first condition. He found that, for primary rays not parallel to the laminations of the model, the central axis depth doses in the model at a half-value layer of 1 mm of Cu were the same as in water for a H.V.L. of 2 mm of Cu. He also found (Boag, 1945) that for fields on the chest there was no difference in the integral dose per röntgen on the skin at the two qualities. He therefore considered that the first condition was adequately fulfilled.

We have not made similar measurements at 8 MeV. However, the average electronic density of the model can be estimated from the chemical formula (C18H18O8) or from a chemical analysis; both lead to an average electronic density in the trunk of 0·90 relative to water. Using the dose at a depth of 10 cm as a rough indication of integral dose, the reduced electronic density would lead to an integral dose about 3·5 per cent too large. At 200 kV the effect of this lack of density will be much greater, and when one considers that in addition the effective atomic number of cellulose acetate is only 6·8, compared with 7·4 for water, Boag's observations on the central axis depth doses appear at first sight surprising. However, the excessive transparency of the model may cause a reduction in the intensity of the scattered rays as well as an increase in the intensity of the primary beam; the net effect can be complex, as has been found by O'Connor (1957) and Jacobsen and Knauer (1956). The second condition is adequately fulfilled at 8 MeV. At 200 kV, however, the low effective atomic number of cellulose acetate seriously affects the response of the chambers. Fig. 10 shows the theoretical response of a small chamber with cellulose acetate walls. Measurements have confirmed the general shape of this response curve. We have used X-rays with a half-value layer of 2 mm of Cu (105 kV effective), but at a depth in the model the effective energy is considerably less; for example at a depth of 12·5 cm on the central axis of a 20 x 20 cm field it is about 72·5 kV (Greening and Wilson, 1951). A large proportion of the total integral dose is contributed by volumes where the dose-rate is very low and the quality soft. A possible approach to the problem is to follow the fate of individual quanta in the phantom until they are photoelectrically absorbed. This is done in Table III by a very rough method, and yields an effective energy of 66·5 kV. However, the calculation is only valid for complete absorption of the X-ray beam, which is by no means the case in the Celluloid Man. The escaping quanta are nearly all degraded. We have taken the effective energy as 75 kV, giving a correction factor of 1·15. A factor of 1·02 is also included to allow for the variation of electronic stopping power.

There seem to be two methods for deriving the integral dose from the measured ionization current:

Method A. This method neglects the failure of condition (1). Equation (1) (with corrections) then gives the r.c.c. received by a water phantom of the same shape and size as the model. A correction must be applied to convert to gm. r/second, since the gm. r is defined as the energy imparted to 1 g of air by 1 r. This correction is equal to the average value of the ratio of the real absorption coefficients per gram of water and air, and is evaluated in Table IV for a half-value layer of 2 mm of Cu. At 8 MeV the ratio is 1·11. To correct to gm. rads, it is assumed that 1 gm. r = 87·5 ergs (W = 34·0).

Method B. This method dispenses with both the conditions that are necessary for the use of equation (1), and evaluates the energy absorbed in the celluloid model itself, using the Bragg-Gray relation E, = ρWf. For a chamber with an air-wall of unit density, when f, is 1 esu/cm³/second, E, is 1 gm. r/cm³/second. In this case we may write:

\[ E_r = 3 \times 10^9 f_r \] if f, is in amp/cm³.

Considering a small element of the model, for each cm³ of air space there is \( \frac{b}{a} \) cm³ of wall material. Therefore, for the small element,

\[ \delta E = 3 \times 10^9 \frac{b}{a} \delta f \]

Integrating over the whole volume of the model,

\[ X = 3 \times 10^9 \frac{b}{a} \text{ gm. r per second} \] (2)

So far the wall material has been considered as equivalent to air of unit density, whereas in fact cellulose acetate has a relative electronic density of 1·056 x 1·3. Allowing for this, and putting equation (2) in the form of (1) with an additional factor,

\[ X = (1·056 \times 1·3 \times \frac{b}{a} + b \delta) (3 \times 10^9 \frac{a + b}{a} \rho f) \] (3)

The first factor is the electronic density of the model averaged over plates and air spaces.

The quantity \( \rho \) allows for the variation of stopping power per electron. This is taken as 1·02 at 200 kV, and is necessary in both methods. At 8 MeV, \( \rho \) is taken as 1·00, allowing 2 per cent for the density effect.

Method B introduces the difficulty that it gives the energy absorption in the model instead of in a water phantom. The effective density of the model is about 0·9 at 8 MeV. At
200 kV the photoelectric and Compton effects are responsible for roughly equal proportions of the energy absorption (see columns 9 and 10 or Table IV) and the effective density can be shown to be about 0.8.

The effect of the change in density can be allowed for in the following way (Fig. 11). Suppose the linear absorption coefficient of the model is a times that of water (a<1). To be shown to be about 0.8.

The effect of the washers and guard ring must now be considered. For energies up to those of the y rays of radium, this can be done by adding further sheets of cellulose acetate build-up zone. Instead, theoretical values calculated from the measured isodose charts have been added to allow for the first centimetre. As a result of these different methods of allowing for the first centimetre, the effective thickness of the model is different for the two energies of radiation. For a given X-ray field, at which the thickness of the model (including guard rings) is x, the effective thickness of the model is (x-2) when the extrapolation method is used and (x-1) at 8 MeV.

Finally, the effect on the isodose surfaces of the laminated construction of the model must be considered. All the most commonly used X-ray fields involve setting the central ray parallel to the laminations, and all the measurements reported here were made in that way. The measurements published by Boag (1945) were made using X-ray beams.

<table>
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<th>No.</th>
<th>E (kV)</th>
<th>θ (deg.)</th>
<th>dE</th>
<th>p (p-e)</th>
<th>No. of Compton recoils</th>
<th>No. of Compton p-e events</th>
<th>δE</th>
<th>δE</th>
<th>Total δE</th>
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<td>2</td>
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Totals: 58:0 47:2 105:2 7000

Effective energy E = \( \frac{\Sigma(E\delta E)}{2\delta E} \) = 66.5 kV

Explanation of Table IV

Column 3: angle of bipartition of scattered quanta.

Column 4: change of energy for scattering at this angle.

Columns 9, 10: allowing for the number of photons still "alive", as in columns 7, 8.

Effective value of \( \frac{gm}{r.c.c.} \) for absorption by the Compton effect = 1.11;

for absorption by the photoelectric effect = \( \frac{(\mu/p)_{water}}{(\mu/p)_{air}} \) = 1.11

Combining these, and weighting for the energy absorption by the two methods,

the mean value = \( \frac{1.11 \times 58 + 1.02 \times 47}{105} \) = 1.07.

Actually a factor 1.06 has been used, based on an earlier assessment. The accuracy of the calculation does not warrant a change of 1 per cent.

field if the field size is itself changed in the same proportion. In general, it can be said that if a beam of X rays falls on the surface of a phantom of density a (in terms of X-ray absorption), with area A on the surface, the proportion of the energy absorbed in the phantom is the same as if a beam of X rays of the same shape and area aA fell in a similar manner on a phantom of unit density, whose linear dimensions are a times those of the first phantom.

There are also various corrections that are common to both methods. A correction is needed for pressure and temperature. At a normal room temperature of 20°C, and at 76 cm of mercury, the factor is 1.07.

The effect of the washers and guard ring must now be considered. For energies up to those of the y rays of radium, this can be done by adding further sheets of cellulose acetate.

Integral Doses at 200 kV and 8 MeV

Figure 13 shows the effect of altering the angle of inclination of beams of various widths applied to various sites, at a H.V.L. of 2 mm of Cu. The width quoted is the field dimension across the laminations. The vertical lines in the figure indicate the half angle of the X-ray beam. Beyond an angulation of this amount no primary ray lies parallel to the laminations. The correction factors quoted are the ratios of the mean ionization currents for angulations greater than the half angle of the beam to those for zero angulation. The disadvantage of performing this experiment on the model is that the thickness traversed by the X-ray beam varies with the angulation. In the region of the stomach, however, the model approximates to a parallel-sided slab. A measurement was also made using a phantom made in the form of a 10 cm cube, constructed in the same way as the Celluloid Man. With the cube fully flooded with radiation, and at 50 cm F.S.D., the ratio of the ionization current with the central ray at right angles to the laminations to that with the central ray parallel to them was 0.885. The general form of these observations is as might be expected; there is insufficient absorption of the rays passing between the laminations, leading to too large an ionization current, particularly for narrow fields and small masses of scattering material. An average factor of 0.925 will be applied here for all field sites and sizes.

The same sorts of experiment have also been performed at 8 MeV. In this case the change in ionization current on exceeding the half angle of the beam was found to be extremely small, but the current with no angulation is

\[
\text{Field size cm:} \begin{array}{|c|c|c|}
\hline
\text{Field size cm} & \text{Measured ionization current} & \text{Ratio} \\
& \text{with beam} & \text{perpendicular to laminations} \\
\hline
4 \times 4 & 46.0 & 48.7 & 1.05 \\
6 \times 6 & 103.3 & 109.7 & 1.06 \\
8 \times 8 & 185 & 189.3 & 1.02 \\
10 \times 10 & 237 & 236 & 0.995 \\
\hline
\end{array}
\]

The effect of the laminations. H.V.L. = 2 mm of Cu.

Comparison of measured and calculated values of integral dose, using Method B. The line gives the calculated values and the crosses represent measurements made with the Celluloid Man.
slightly the smaller of the two, in contradistinction to the position at 200 kV. Measurements were also taken with the 10 cm cube phantom, also at 100 cm F.S.D., with the results shown in Table V.

These measurements confirm that a smaller ionization current is measured when the rays are parallel to the laminations. However, the effect when using the model is so small that it will be neglected in calculating the results. Table VI summarises all the corrections:

It turns out that both methods A and B give equally good agreement with calculated values. All the values quoted in the body of this paper were obtained by using method A, which was also the method used by Boag. Figure 14 compares measured and calculated values using method B, for fields on the head and pelvis. The reasonable agreement obtained with both methods may perhaps be considered to strengthen confidence in the validity of all the methods of estimation used in this paper.
THE PERFORMANCE OF THE MEDICAL RESEARCH COUNCIL 8 MeV LINEAR ACCELERATOR

By G. R. NEWBERY and D. K. BEWLEY

Vol. XXVIII, No. 329, MAY, 1955
THE PERFORMANCE OF THE MEDICAL RESEARCH COUNCIL
8 MeV LINEAR ACCELERATOR


Radiotherapeutic Research Unit of the Medical Research Council, and the Physics Department
Hammersmith Hospital, London, W.12

(Accepted for publication September, 1954, but revised to December, 1954)

T
he first travelling wave linear electron accelerator was successfully operated by Fry and his team in 1948. Following this, the Medical Research Council, in collaboration with the Ministry of Supply, placed a contract with Metropolitan-Vickers Electrical Co. Ltd. for a linear accelerator suitable for clinical use. The design of this machine was carried out by Metropolitan-Vickers in conjunction with Fry and his team and with members of the Radiotherapeutic Research Unit of the Medical Research Council.

The Medical Research Council accelerator first operated at the end of 1950 and an exhaustive series of tests was carried out at the Metropolitan-Vickers laboratories over the period 1951-52. The machine was installed at Hammersmith Hospital during 1952 and was handed over to the Medical Research Council in February 1953. Technical details have already been described by Miller (1953 and 1954) and a brief survey of the installation has been published by Wood and Newbery (1954).

A programme of physical measurements was started in February 1953 and patients have been treated continuously since September 1953.

The purpose of this paper is to describe the installation in detail, to present the results of the physical measurements and to report on the operation of the machine.

The layout of the machine

Fig. 1 shows the layout of the linear accelerator suite in the new building recently completed for the Medical Research Council at Hammersmith Hospital, London. This suite consists of control rooms, treatment room, and a maintenance laboratory; adjacent to the suite are waiting rooms, examination rooms, planning rooms and offices. There is also a measuring room, which contains a couch similar to that in the treatment room, and a gantry carrying a diagnostic X-ray set, diaphragms, optical system and front and back pointers similar to those on the linear accelerator. The range of movements is the same as in the treatment room, and this enables patients to be marked and radiographed in the positions they will actually assume during treatment, without reducing the available treatment time of the machine.

The treatment room is shown in Fig. 2. The accelerator extends 8 ft. into the room, where it is supported entirely from the ceiling, leaving the floor clear. Before striking the target, the high energy electron beam is bent through 90 deg. by an electromagnet, which is mounted in an X-ray head which can be rotated through 120 deg.; the X-ray beam can thus be directed at any angle from 15 deg. above the horizontal to 15 deg. beyond the vertical, in a plane perpendicular to the axis of the accelerating tube. The X-ray beam, produced by the electrons hitting a full-range gold transmission target, is collimated by a conical aperture in fixed uranium and tungsten-copper alloy blocks within the X-ray head. This limits the beam to a diameter of about 26 cm at 1 m from the target. The treatment field size at 1 m can be adjusted from a 4 cm square to a 20 cm square, or any intermediate rectangle, by means of 3 in. thick adjustable diaphragms of tungsten-copper alloy. The outer surfaces of these diaphragms are 45 cm from the target. Circular fields can be obtained by fitting inserts into the adjustable diaphragms. A retractable front pointer and a removable back pointer, which can be seen in Fig. 2, indicate the central axis of the X-ray beam. There is also an optical system which illuminates the area of the patient's skin on which the X rays fall.

The patient lies on a special adjustable couch, which is mounted on a traversing mechanism underneath the floor. The top of the couch is fitted with horizontal slides having a large range of movement (42 in. longitudinal, 15 in. transverse). There is also a rotational movement, which can be motor-driven for rotation therapy. The axis of rotation normally passes through the end of the front pointer. The whole treatment-room floor rises or falls a distance of 2 ft. 6 in. from the mean level, and this, together with the movement of the couch top, enables the patient to be positioned relative to the machine, so that the front pointer is brought to the planned entry point on the patient's skin. The rotation of the X-ray head automatically controls the vertical movement of the floor and the horizontal traversing movement of the couch, so that the beam direction can be adjusted without disturbing the setting of the entry point, as described by Flanders and Newbery (1950). A simplified technical explanation
of these automatic controls has recently been published (Technique, 1954). The treatment couch has the usual tilting end and clamps for holding the patient in position. There are also two other special features: a removable treatment chair (as shown in Fig. 19) and an adjustable central gap (as shown in Fig. 2). The latter enables the back pointer method of checking beam direction to be used even with the X-ray beam vertical.

The clinical control room has been kept as simple as possible and is as easy to use as that of a conventional 200 kV X-ray therapy machine. There are two main switches, one for the radio-frequency system, the other for the electron gun. The required dose (absorbed dose in soft tissue, 2 cm below the surface) can be set in steps of 10 rads up to a maximum of 600 rads, and the machine automatically switches itself off when the set dose has been administered. A large circular meter in the centre of the control room is used to indicate the time remaining.

The angle of the X-ray beam, the independent vertical adjustment of the floor, and the intensity of the optical illumination, are controlled from the small mobile pedestal, which can be seen in Fig. 2. The treatment room is surrounded by concrete walls 4 to 6 ft. thick. Access is obtained by means of an indirect corridor, at the safe end of which is the clinical control room containing the control desk, shown in Fig. 3. This is adjacent to a 12 in. dia. air tunnel through the concrete wall, through which the patient can be kept under observation during treatment by means of a periscope system, as shown in Figs. 3 and 4.

The clinical control desk has been kept as simple as possible and is as easy to use as that of a conventional 200 kV X-ray therapy machine. There are...
The Performance of the Medical Research Council 8 MeV Linear Accelerator

of the desk indicates the total dose. Meters also indicate the dose-rate and the exit dose. The total dose and dose-rate signals are obtained from parallel plate ionization chambers in the X-ray head. The exit dose signal is obtained from a thin-walled Perspex chamber which can be positioned by the radiographer. Each chamber has its own d.c. amplifier. There is also the usual form of intercommunication between the control desk and the treatment room.

Protection measurements

The thicknesses of protective material in the X-ray head were specified by Flanders (1949, 1951) to reduce the dose-rate in all directions to 0.2 per cent of that in the main beam. Measurements were made around the X-ray head with the diaphragms completely closed and the machine operating under conditions which would give a central axis dose-rate of 100 rads per min, at 2 cm deep in a water phantom with its surface at 1 m from the target. The X-ray head was surrounded by envelope-wrapped X-ray film and a small thick-walled ionization chamber was moved round it at 1 m from the target. It was found that in nearly all directions the dose-rate was, in fact, not more than 0.2 rads/min. There were, however, two very small areas of leakage where the dose-rate was about 1 rad/min. These are both away from the direction in which the patient lies and are of no significance. The contribution of the leakage radiation to the integral doses given by this machine will be dealt with in a later paper.

A protection survey was made using a d.c. amplifier and a 7 litre ionization chamber with 1 in. thick walls of graphited polythene. The maximum dose-rates are shown in Fig. 1, and it can be seen that at all places where staff could be present while the machine is on the dose-rate is well below the maximum permissible level. Table I shows the dose-rates at various points for a vertical and a horizontal beam, with and without a phantom to represent a patient. These measurements were made with the machine operating so as to give a dose-rate of 100 rads/min at 1 m and with a 20 x 20 cm field size.

Measurements were also made with an unshielded scintillation counter (EKCO type N509) with a sodium iodide crystal of 1-3 cm² target area and an unshielded GM4 Geiger counter of 4 cm² target area. The machine was operated under the
same conditions, with a horizontal beam striking a wax phantom. At the edge of the clinical control desk near to the observation window the counting rate with the Geiger counter was increased by 83 counts/min when the linear accelerator was switched on. The corresponding figure for the scintillation counter was 4000 counts/min. In the first floor laboratory, nearest to the linear accelerator, the counting rate with the scintillation counter was increased by about 30 counts/min when the machine was switched on. On the second floor the observed increase was 2 counts/min in a count of about 1500 in 10 min. From the latter observation there is a 95 per cent probability that the true counting rate due to the linear accelerator is less than 11 counts/min. The counting rate to be expected on the first floor with an unshielded Geiger counter of 10 cm² target area is thus 1.5 counts/min. Since 2 in. of lead local shielding is at least 3 H.V.L.s, the counting rates due to the linear accelerator are well below the design criterion and there will not be any interference with measurements using Geiger counters anywhere on the first or second floor of the building.

**Beam centralising**

Since the whole X-ray head, containing the electromagnet and target, rotates in a plane perpendicular to the axis of the accelerating tube, it is essential that the electron beam should enter the electromagnet exactly on the axis of rotation if the focal spot is to remain fixed on the target at all angles of the X-ray head. If the spot is allowed to move, the intensity distribution across the X-ray beam becomes dependent on the angle of the head. In order to centralise the electron beam, and to eliminate this dependence upon the angle of the head, a special

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**TABLE I**

<table>
<thead>
<tr>
<th>Position</th>
<th>Dose rate in units of the maximum permissible level, (T=2 \times 10^{-6}) rads/sec (=0.3 rad/week) for 100 rads/min at 1 m from target on axis of beam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without phantom</td>
</tr>
<tr>
<td>A. Between treatment room corridor doors</td>
<td>0.01</td>
</tr>
<tr>
<td>B. At control room end of gangway</td>
<td>0.12</td>
</tr>
<tr>
<td>C. On gangway in line with X-ray head</td>
<td>1.4</td>
</tr>
<tr>
<td>D. At treatment room end of gangway</td>
<td>17</td>
</tr>
<tr>
<td>E. At entry to pump room</td>
<td>0.5</td>
</tr>
<tr>
<td>F. At pump room end of viewing tunnel</td>
<td>0.7</td>
</tr>
</tbody>
</table>

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**Fig. 4.**

Diagram of the periscope system for viewing the patient from the control desk during treatment.
A 25-way chamber was constructed. This chamber was made of Perspex and contained a coin-shaped air volume 26 cm dia. and 2 mm deep, with the necessary surfaces graphited, and with the front wall 2 cm thick. The front surface of the air volume was connected to a polarising voltage and the lower surface was earthed. Within the lower surface, 25 areas each 2 mm dia. were insulated by small grooves; these areas were at 6, 9 and 12 cm radius and were arranged on eight radial lines at 45 deg. intervals. There was also an insulated area at the centre. Each of these insulated areas was connected, by means of a separate concentric screened cable, to a selector switch in the control room, which, in turn, was connected to a d.c. amplifier. The whole chamber was attached to the X-ray head, with the air volume at 102 cm from the target, as shown in Fig. 5. This made it possible to measure, very rapidly, the distribution of intensity transverse to the central axis of the X-ray beam, at any desired angle of the X-ray head. The position of the electron beam can be altered by means of four pairs of centralising coils, and by adjusting the current through them it was possible to make the transverse distribution of intensity constant to within 3 per cent for any position of the X-ray head. The variation of the ratio of the dose-rate in the vertical to the horizontal position of the X-ray beam is shown in Table II. Only two pairs of centralising coils were in fact used.

**Beam flattening**

When the electron beam had been centralised, it was found that the X-ray intensity was greatest near the centre of the X-ray beam, due to the well known form of the polar diagram for high energy X-ray production. However, it was also found that the distribution of intensity across the X-ray beam was not symmetrical; the most probable cause is explained in Fig. 6. The electron energy spectrum is not symmetrical (Miller, 1953, 1954), and there is a tail of low energy electrons which is bent further across the target than the peak of the spectrum. These low energy electrons produce X-rays, which are screened by the fixed collimating material to a greater extent on the one side than they are on the other. These two effects were eliminated by inserting a special skew conical aluminium filter in the X-ray beam.

**Table II**

<table>
<thead>
<tr>
<th>Direction of radius</th>
<th>Radial distance</th>
<th>Radial distance</th>
<th>Radial distance</th>
<th>Radial distance</th>
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<tr>
<td></td>
<td>6 cm</td>
<td>9 cm</td>
<td>12 cm</td>
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<td>0°</td>
<td>1.00</td>
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<td>1.02</td>
</tr>
<tr>
<td>45°</td>
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<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>90°</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>135°</td>
<td>0.995</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>180°</td>
<td>0.995</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>225°</td>
<td>0.995</td>
<td>1.00</td>
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<td>0.975</td>
</tr>
<tr>
<td>270°</td>
<td>1.015</td>
<td>1.00</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>315°</td>
<td>1.015</td>
<td>0.995</td>
<td>1.00</td>
<td>1.02</td>
</tr>
</tbody>
</table>

**Note**—The 180° radius is always in the direction of acceleration of the electrons.
beam immediately above the ionization chamber; its shape is shown in Fig. 7. The correct shape of this filter was found by measuring the transverse distribution of X-ray intensity, using a single chamber operated by the remote control apparatus described below. The filter was designed to overcompensate the large fields so that even quite small fields should be reasonably flat. Isodose curves, shown in Figs. 10, 11, 12 and 13, show the extent to which this was successful.

It is convenient at this point to make a summary of the difficulties introduced by bending the electrons through a right angle before they strike the target. Firstly, the electron beam must enter the magnet on its axis of rotation if the X-ray distribution is to be the same at all angles of the X-ray head. The position of the electron beam must be adjusted not to give a symmetrical X-ray distribution at any one angle of the head, but to give a constant distribution at all angles.

Next, the current through the deflector magnet must be set to bring the electron beam on to the target centrally with respect to the conical hole in the fixed collimating blocks. If this is not done, and many of the electrons strike the target behind the collimator, there will be a severe drop in X-ray intensity near the edge of the beam on that side, as shown in Fig. 6. The correct setting for any given electron energy is obtained by adjusting the magnet current to give maximum X-ray output, as measured by the parallel plate chamber in the X-ray head.

Finally, since the magnet spreads out the electron spectrum, any asymmetry in this has to be corrected by a skew filter in the X-ray beam.

Isodose curves
Isodose curves were measured with a horizontal X-ray beam, using an ionization chamber which could be moved in an 18 in. cube water phantom with Perspex walls. The maximum ionization occurs at a depth of a little less than 2 cm and the centre of the measuring volume could be brought to within 9 mm of the front surface. The chamber was driven by magslips, the signals for which were derived from identical magslips connected to an essentially
similar remote control apparatus. This remote control apparatus is shown in Fig. 8 and is described in greater detail elsewhere (Bewley, 1954). It contains a pair of cross wires, whose movements are followed by the ionization chamber. A lamp and parabolic mirror below the cross wires cast an unmagnified shadow on to a ground glass screen (not shown) mounted above. A sheet of graph paper can be attached to the ground glass screen, and, as the intersection of the shadows of the cross wires (shown at X) always represents the position of the chamber, the measurements can be plotted directly. The ionization current was measured on a battery-operated d.c. amplifier of the type described by Wyard (1950). A sensitivity adjustment enabled the meter reading to be set to 100 when the chamber was on the peak of the central axis depth dose curve (normally taken as being at a depth of 2 cm), so that the meter readings gave percentage depth doses directly. We have found this system of measurement to be very flexible and extremely satisfactory.

Most of the measurements were made using a Perspex chamber, shown in Fig. 9, which was made waterproof by using rubber O-rings in its construction. It has an air volume of $5 \times 2 \times 2$ mm, the 5 mm dimension being arranged parallel to the edge of the beam, so that the effective chamber width in crossing the edge of the beam was 2 mm. Isodose curves obtained by this means are shown in Figs. 10–13.

The dose near the surface was obtained in two ways. Firstly, by using a chamber having a front wall of cellophane 0.02 mm thick and adding sheets of Perspex above it. Secondly, by means of another Perspex chamber, similar to that shown in Fig. 9, but with a 0.12 mm thick front surface and an air volume 5 mm dia. x 2 mm deep. The latter was used with a vertical X-ray beam and was moved up and down in a water phantom by means of a remotely controlled traversing gear. The ionization current when the chamber was close to the surface was found to depend slightly on the polarity of the applied voltage; mean values have been used.

It was found that the isodose curves were not absolutely symmetrical. The asymmetry depended on the deflector magnet current, but was partly due to lack of perfection in the flattening filter. Since the 25-way chamber showed that the transverse distribution in the vertical plane was slightly different from that in the horizontal plane, no attempt was made to eliminate the asymmetry below a few per cent. The isodose curves shown in Figs. 11, 12 and 13 were made symmetrical by taking the mean of values on each side of the axis. These isodose curves are used in clinical work and do not introduce an inaccuracy of more than 3 per cent.

Central axis percentage depth doses for various field sizes are given in Table III. It can be seen that there is only a slight variation with field size.
G. R. Newbery and D. K. Bewley

The build-up curve between the surface and the peak has been investigated at a number of distances from the target, and the variation has been found to be quite small, as shown in Fig. 14. This is in agreement with the work of Miller and Howarth (Miller, 1950; Howarth, 1951). It is planned to make extension inserts for the diaphragm system, to provide small fields with a penumbra less than that associated with the diaphragm system as used at present. The penumbra for a 10 cm wide field can be seen, from Fig. 12, to be 1.5 cm between the 90 and 10 per cent contours at the level of the peak.

Outside the main beam there is a greater dose-rate than would be expected from geometrical considerations. Near the surface the low-level isodose lines curve outwards, presumably owing to recoil

![Isodose chart for 6 x 6 cm field 1 m F.S.D. with final flattening filter in position.](image1)

![Isodose chart for 10 x 10 cm field 1 m F.S.D. with final flattening filter in position.](image2)

![Isodose chart for 20 x 20 cm field 1 m F.S.D. with final flattening filter in position.](image3)

**TABLE III**

<table>
<thead>
<tr>
<th>Depth</th>
<th>4 x 4</th>
<th>6 x 6</th>
<th>8 x 8</th>
<th>10 x 10</th>
<th>12 x 12</th>
<th>15 x 15</th>
<th>20 x 20</th>
</tr>
</thead>
<tbody>
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<td>11</td>
<td>13</td>
<td>15</td>
<td>17</td>
<td>20.5</td>
<td>24</td>
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<tr>
<td>2 mm</td>
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<td>48</td>
<td>49</td>
<td>51</td>
<td>54</td>
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<tr>
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<td>74</td>
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<td>77</td>
<td>78</td>
<td>80</td>
</tr>
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<td>92:5</td>
<td>93</td>
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<td>97:5</td>
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<td>46</td>
<td>47:5</td>
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<tr>
<td>20 cm</td>
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<td>37:5</td>
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<td>25 cm</td>
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<tr>
<td>30 cm</td>
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<td>23:5</td>
<td>25</td>
<td>26:5</td>
<td>27:5</td>
<td>28:5</td>
<td>29:5</td>
</tr>
</tbody>
</table>

Narrow beam absorption measurements give the following characteristics of the radiation: in lead, \( \mu = 0.52 \text{ cm}^{-1} \), or 1.33 cm H.V.L.; and in water, \( \mu = 0.043 \text{ cm}^{-1} \), or 16.3 cm H.V.L. The values for water give an effective quantum energy of 2.6 MeV.
The Performance of the Medical Research Council 8 MeV Linear Accelerator

Electrons coming from the air or from the surface of the diaphragms. These electrons can be absorbed by \( \frac{1}{18} \) in. of lead, and in clinical use it is occasionally necessary to make a lead mask to cover some area outside the main X-ray beam. At greater depths, the additional dose-rate outside the beam is due to scattered X rays. Fig. 15 is designed to show the way in which these arise. The intensity outside the phantom. In addition, the radiation penetrating the diaphragms when completely closed is shown in the lowest curve; it can be seen that for a 10 cm field in air there is a considerable additional quantity of radiation, which consists of hard X rays scattered from the filter, diaphragms and collimating system through the aperture of the diaphragms. The effect increases rapidly with field size, and it will be

![Graph](image_url)

**Fig. 14.**
The build-up curve in Perspex for an 8 x 8 cm field at two distances from the target. The front wall of the chamber consisted of graphited cellophane of 0.02 mm thickness.

![Graph](image_url)

**Fig. 15.**
The percentage dose-rate outside the main X-ray beam, at 102 cm from the target under various conditions.

![Graph](image_url)

**Fig. 16.**
Isodose chart for a 10 x 10 cm field at 30 deg. oblique incidence to surface of the phantom.

![Graph](image_url)

**Fig. 17.**
A non-opposed two-field distribution for the treatment of Ca. bronchus. Note the low skin and spinal cord doses.

Beam "in air" and at a depth of 2 cm in a water phantom is plotted against radial distance. The measurements "in air" were made with the chamber covered by a cylindrical polythene cap with a 2.25 cm wall. The difference between the curves represents the contribution due to scatter from the considered in greater detail in a later paper with particular reference to its effect on integral doses.

Isodose curves in a water phantom have also been measured with the X-ray beam at oblique incidence; such a curve is shown in Fig. 16. Depth dose measurements have shown that below the peak
the fall of dose with depth due to absorption is very roughly equal to that due to the operation of the inverse square law. As a result, with an oblique X-ray field, the isodose lines below the peak lie about halfway between the angle of the surface and the direction perpendicular to the axis of the beam. This provides a convenient principle for treatment planning. In front of the peak it is usually assumed that the isodose lines are parallel to the skin.

Details of treatment planning will be given in a later paper, but Fig. 17 shows the type of dose distribution which can be obtained with as few as two fields. It is hoped to improve the uniformity of the tumour dose in this technique by using a wedge filter.

The calibration of the dose meter has been carried out with a bakelite-graphite ionization chamber connected to a d.c. amplifier and it has also been checked with condenser chambers of different designs. The ionization current was compared with that produced when the chamber was placed at the centre of a 10 cm dia. ring of 40 × 5 mg radium tubes, whose content had been measured by the Radiochemical Centre, Amersham. The radium tubes were placed in a circular jig containing the least possible amount of scattering material. Subsidiary experiments showed that scattering was negligible both from the jig and the tubes and that the jig was large enough in relation to the size of the chamber. Values of 8-3 r/h at 1 cm from 1 mg of radium and 93 ergs/g in water for 1 r have been used. This calibration method has recently been checked by measuring the output of a number of megavoltage machines at other centres, and has given values within 3 per cent of the latest N.P.L. figures to be used by these centres (December, 1954).

It is also intended that the dose meter calibration should be checked by the use of a special ionization chamber in which both the effective volume and the wall material can be varied in a number of different ways; this will be independent of a radium standard.

In clinical use a dose-rate of 100 rads/min is used with the machine running at 350 pulses/sec. The built-in stabiliser maintains this output to within ±2 per cent. For accurate measurements a fine control has been installed in the stabiliser with which ±1 per cent can easily be achieved. Every day a comparison is made between the indication of the dose meter and the product of the dose-rate meter reading and the time of exposure. This ensures that neither d.c. amplifier has seriously changed its performance. As a further check, a calibration against radium is carried out using another ionization chamber at least once a month. The built-in dose meter has been found to be very closely linear for doses above 100 rads, and the tripping arrangement trips out correctly to within 2 per cent. By doing a daily calibration, it has been found that the output does not vary by more than 3 per cent over several weeks.

**Operation and running experience**

Since September 1953, the machine has been running to a routine schedule. Each day the filaments and focusing coils, which require a long time to warm up, are automatically switched on at 7 a.m. At 9 a.m. a technician switches on the machine; he checks the R.F. switches on the machine; he checks the R.F. output and frequency, the X-ray output, and the operation of the dose meter and...
tripping circuits. Provided that these are satisfactory, he then transfers the control of the machine from the maintenance laboratory to the radiographer’s control desk. The radiographer then operates the machine for the rest of the treatment period. The technician is free to do other work, but remains on call. The running-up and checking of the machine normally takes about ten minutes.

In the three months from September 1953 to December 1953, about 50 patients started treatment. During the 12 months of 1954 about 350 patients were treated. During these 15 months there has been only one day on which a fault in the machine has prevented the prescribed daily treatments from being given to several patients, although there have been a number of occasions when a fault has caused some delay during the treatment period. There have also been a number of other electrical and mechanical faults, which have not interfered with treatment and which could be remedied at the end of the treatment period. Such faults are inevitable in a first machine, but there has been a notable absence of any major mechanical or electrical faults, with the exception of troubles arising from the ignitrons as described below.

The life of the 2 MW magnetrons has been extremely satisfactory. Two of these valves are in use; one has operated over 1500 hours and the other over 200 hours. The ignitrons, however, have caused considerably more trouble, but fortunately their cost is only about a fifth of that of a magnetron. The igniton is the mercury switch which is used to pass the current pulse from the H.T. supply through the magnetron via the pulse transformer. At first, these ignitrons had a very short life; often they would fail to strike after less than 50 hours of running. However, by increasing the striker current from 150 to 250 amp the average life has been increased to the order of 200 hours. There has been very little trouble due to ignitrons firing through and so causing the machine to trip out.

Maintenance of the machine is carried out on a routine basis after the treatment sessions and on Saturday mornings.

The clinical facilities of the machine have all proved fundamentally satisfactory, but a few detailed mechanical improvements have been necessary. The treatment couch and, in particular, the treatment chair have been found very convenient to use. The treatment chair, which fits on to the couch, is shown in use for the treatment of a bronchus case in Fig. 19. As expected, it has been found that setting-up is considerably simplified by being able to adjust the beam direction without disturbing the setting of the entry field.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the contributions made to this work by Mr. F. D. Pilling, who has constructed most of the ionization chambers and apparatus used in the measurements described above, and by Mr. E. A. Wojciekiewicz, who was responsible for the maintenance of the machine and who has also assisted with the measurements.

SUMMARY

The 8 MeV linear accelerator of the Medical Research Council, which is installed at Hammersmith Hospital, London, is described. An account is given of the physical measurements which have been made to enable the best use to be made of the machine for X-ray therapy. These measurements include work on protection, beam flattening, output calibration and isodose curves. The machine normally gives a stabilised dose-rate of 100 rads/min at 2 cm deep in a water phantom with its surface at 1 m from the target. Four hundred patients were treated between September 1953 and December 1954. A report is made on the operation of the machine, which has been very satisfactory.

REFERENCES

ELECTRON THERAPY AT 8 MeV


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Electrons in the form of \( \beta \) radiation have been employed for many years in the treatment of disease affecting the skin and superficial tissues. The source of the radiation may be one of the many \( \beta \)-emitting radioactive isotopes. As the maximum depth of penetration of the electrons from these sources is only a few millimetres, this form of therapy has a limited application but may be used in the treatment of benign skin conditions, of superficial rodent ulcers, and of diseases affecting the conjunctiva and cornea, where irradiation of the lens is undesirable.

With the development of supervoltage apparatus, it was possible to produce and extract electron beams capable of penetrating several centimetres of tissue. A number of reports on therapeutic applications of beams of electrons produced by the Van de Graff generator and the betatron have now been published (Trump, Wright, Evans, Anson, Hare, Fromer, Jaque and Horne, 1953; Haas, Harvey, Laughlin, Beattie and Henderson, 1954; Becker and Weitzel, 1956).

When the 8 MeV prototype linear accelerator was designed in collaboration with the M.R.C. Radiotherapeutic Research Unit, the possibility of using the electron beam was anticipated and provision was made for its extraction from the machine, although it was realised that it might have only a limited application therapeutically.

When the machine is used for X-ray therapy an electromagnet deflects the electrons through a right angle before they strike the target. If the magnet is not energised, the electrons continue in a straight line and pass through an aluminium window and then through an aperture in the protective housing of the machine into the treatment room. During X-ray therapy this aperture is blocked with a heavy alloy plug. The extracted electron beam is horizontal and in a fixed position and the patient has to be adjusted to the correct height by means of the rising floor of the treatment room.

Scattering and collimation

The electrons emerge as a pencil of radiation less than 1 cm in diameter. In order to give a uniform treatment over a reasonable area the beam must be spread out and we have done this by passing it through a scattering foil of gold, 0.11 mm in thickness. The divergent beam is confined by a Dural cylinder, at the far end of which a diaphragm limits the irradiated area on the patient. The end of this treatment cylinder is shown in Fig. 1 and a photograph of the apparatus is shown in Fig. 2. The cylinder is 1 m long, 25 cm (10 in.) in diameter and 0.475 cm (\( \frac{3}{16} \) in.) thick. A stop near the machine end limits the irradiation of the wall to one third of its length, at the treatment end. Few electrons penetrate through the wall of the cylinder because of the extremely oblique incidence. The dose on the outside, near the treatment end, is 5 per cent of the surface dose in the irradiated field.

The size of the field is defined by a hole cut in an aluminium plate, which is fitted into slots at the end of the treatment cylinder. The plate is \( \frac{3}{8} \) in. (1.6 cm) thick, which is just sufficient to stop the electrons. This diaphragm can be turned about the axis of the cylinder for convenience in setting-up the patient. The largest field size available is 17.75 x 24.5 cm with curved ends, as shown in Fig. 1. The aluminium diaphragm cannot normally be brought into contact with the patient’s skin and collimation is completed by means of Perspex walls, a few centimetres in length (Fig. 3). By intercepting scattered electrons, the sharpness of the edge of the field is improved.

It is also possible to define the beam with a lead mask laid directly on the patient. The minimum thickness of lead needed to stop the electrons is 3.7 mm. The dose-rate due to X rays behind the lead is 2.5 per cent of the dose-rate due to electrons, compared with 1 per cent in the case of aluminium.

It is not satisfactory to limit the beam solely by means of a collimator placed close to the scattering foil, because the treatment area does not then receive uniform irradiation. This is a result of scattering by the air between the foil and the patient. Fig. 4 shows the radiation distribution across a 15 cm diameter field, at a depth of 2 cm, for four different collimation systems. The field area was defined by an aluminium diaphragm at the surface of the water phantom and no other collimation was used in the case of curve 3. The effect of additional aluminium

332
Electron Therapy at 8 MeV

The end of the treatment cylinder nearest to the patient, showing the diaphragm and monitoring ionization chamber.

A Ionization chamber (graphited Perspex).
B Slots for diaphragm (brass).
C Rotating assembly (brass).
D Locking screw.
E Cylinder, 1 m long (Dural).
F Main diaphragm (Dural).

collimators placed 6 cm from the scattering foil is shown by curves 1 and 2. The collimating apertures were conical, with the apex in each case on the scattering foil. The projected apertures at the water phantom were 19 and 29 cm in diameter. It will be seen that the irradiation is not uniform even with a beam twice the diameter needed to cover the desired field. Curve 4 was measured using the treatment cylinder and in this case scattering in from the walls of the cylinder helped to give a uniform irradiation.

Radiation distributions

The gold foil provides adequate scattering of the electron beam with a minimum loss of energy. If a
less penetrating beam is wanted, the energy of the electrons can be reduced by passing them through a block of carbon which is inserted instead of the scattering foil. Figure 5 shows the central axis depth dose curves in water for a 12 cm diameter field using the gold scattering foil and using a carbon decelerator 1.5 cm thick. At the full energy of the beam, the depth dose rises to a rather flat maximum at a depth of 1.5 cm. From the surface to a depth of 2.4 cm the dose is uniform to within 20 per cent and at greater depths the depth dose falls rapidly to a level determined by the X-ray flux. The surface dose is between 80 and 100 per cent of the peak value, depending on field area and conditions of collimation.

The form of the central axis depth dose curve is similar for all field sizes down to 4 cm diameter. With very small fields the zone of almost constant irradiation disappears and the dose decreases steadily with depth.

Table I gives some information on the dose due to X rays under various conditions.

<table>
<thead>
<tr>
<th>Scattering or decelerating material</th>
<th>Total thickness g/cm²</th>
<th>X-ray dose as % of electron dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11 mm gold</td>
<td>0.22</td>
<td>1.0</td>
</tr>
<tr>
<td>0.11 mm gold followed by 15 mm carbon</td>
<td>2.7</td>
<td>2.1</td>
</tr>
<tr>
<td>15 mm carbon alone</td>
<td>2.5</td>
<td>1.1</td>
</tr>
<tr>
<td>0.11 mm gold followed by 10 mm aluminium</td>
<td>2.9</td>
<td>4.0</td>
</tr>
<tr>
<td>10 mm aluminium alone</td>
<td>2.7</td>
<td>2.6</td>
</tr>
</tbody>
</table>

These measurements were made in a water phantom placed at the end of the treatment cylinder, at 120 cm from the scattering and decelerating materials, with a 12 cm diameter field. The dose rate of the X rays was taken as the ionization at a depth of 5 cm for the gold foil and otherwise at a depth of 3 cm, these depths being a little greater than the penetration of the electrons.

Dose monitors and calibration

The dose received by the patient is monitored by a pair of ionization chambers at the treatment end of the Dural tube, as shown in Fig. 1. The chambers are connected in parallel, and they intercept a fraction of the beam. The integrated dose is displayed on a meter built into the control desk.

We have investigated other methods of monitoring the beam but they were less satisfactory at high dose-rates and we considered that the monitor should operate reasonably well even at the maximum output of which the machine is capable, i.e. 50,000 r/minute at the patient's skin. It would be difficult to measure such high dose-rates with a transmission chamber. If the chamber were placed near the scattering foil, the dose per pulse would be about 10⁴ r, and if placed nearer the patient it would be difficult to maintain close spacing of the plates over the larger area. We have also considered using as a monitor the charge collected by the scattering foil. The beam ejects secondary electrons from the foil, giving it a positive charge. The current obtainable from the foil is directly proportional to the intensity of the beam if the foil is maintained at +0.3 V. We have compared the current from the foil with that from an ionization chamber on the surface of a phantom at a distance of 1 m, and we found that the ratio of these currents varied unpredictably from day to day. Also, under certain conditions the foil gave a negative current, presumably owing to low energy electrons emerging from the machine.

The standard for dosimetry is a Baldwin-Farmer sub-standard dosemeter with the chamber at a depth of 1.5 cm in a tissue-equivalent phantom. Negative polarity gives a reading 1 per cent greater than does positive polarity. The collection efficiency of the chamber is over 97 per cent at the dose-rates used for treatment and calibration, which lie in the range 100 to 600 rads per minute. The Baldwin-Farmer chamber has been calibrated in röntgens against radium tubes of known content, and at the National Physical Laboratory with a 2 MeV generator. The two calibrations agree to within 1 per cent.

The derivation of absorbed doses in water is complicated by the fact that the stopping power of water relative to that of air varies considerably with electron energy, mainly owing to the density effect. At present we are assuming that when the ionization in the chamber (irradiated with the electron beam) is the same as that due to 1 röntgen of radium γ rays, the absorbed dose in water is 86.5 ergs per gram. The use of this figure puts the dosimetry of the electron beam on a similar basis to that of the X-ray beam (Newbery and Bewley, 1955). The energy required to form an ion-pair in air is taken as 32.5 eV, and a correction of 7 per cent is applied to allow for the density effect at 4 MeV, taken as the average energy of the electrons. The true value of the absorbed dose is probably about 5 per cent greater than that indicated. However, the use of a thimble chamber in this way is not very
satisfactory and a more absolute method of calibration is needed.

**Safety precautions**

Because of the enormous dose-rates that the machine can provide, special precautions are taken to prevent a patient from being accidentally overdosed. A system of interlocks ensures that a separate filament control is used for controlling the dose-rate during electron therapy, and this control is normally pre-set with a fine control covering a range of 2 to 1 in dose-rate. Before taking the patient into the

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**FIG. 4.** Uniformity of irradiation of 15 cm diameter field at a depth of 2 cm in water.

Curve 1, with collimator giving projected area 19 cm in diameter at the phantom.
Curve 2, with collimator giving projected area 29 cm in diameter at the phantom.
Curve 3, no collimator.
Curve 4, using the treatment cylinder.
Curves 1, 2 and 3 were measured with a copper scattering foil, 0.19 g/cm² in thickness, and curve 4 with a gold foil 0.22 g/cm².

**FIG. 5.** Central axis depth dose curves in water for a 12 cm diameter field, with (a) a gold scattering foil 0.11 mm thick, (b) a carbon decelerator 1.5 cm thick.

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**FIG. 6.** Isodose chart for a circular field 12 cm in diameter. The final collimation was by means of a Perspex tube with walls 3 mm thick. The 5 per cent isodose line shows the effect of electrons penetrating the wall of the tube.

**FIG. 7.** Isodose chart for a circular field 5.7 cm in diameter. The final collimation was by means of a Perspex tube with walls 6 mm thick.
treatment room the radiographer (a) checks that the filament current is within the prescribed range, (b) checks that the dose monitor is working, (c) measures the time needed to deliver 200 rads and checks it against the time expected for that particular filament current.

We have not had any serious difficulties in delivering the treatments so far. At the beginning we were using a lead foil as the scattering material, and it punctured due to overheating during an experimental irradiation. We did not notice this for a few days, and it resulted in an uncertainty of 10 per cent in the dose received by the first patient. This occurred because the dose distribution is not uniform when the scattering foil is absent or too thin, and under these conditions the monitoring chamber underestimates the dose at the centre of the treatment area. The gold foil shows no signs whatever of deterioration even after many hours of running of the machine at maximum output.

CHARACTERISTICS OF THE ELECTRON BEAM WITH REFERENCE TO THERAPY

Isodose charts measured in a water phantom placed at the end of the treatment cylinder are shown in Figs. 6 and 7.

Figure 8 shows the effect of oblique incidence. It is an isodose chart for a cylindrical phantom 15 cm in diameter, irradiated perpendicular to its axis. Photographic film was used, the film being inclined at a small angle to the incident electrons. The irradiated zone becomes narrower and the peak intensity becomes slightly greater as the rays become more oblique.

The 8 MeV electron beam has the following characteristics:
1. Over the first 2.4 cm the dose is uniform to within \pm 10 per cent and we consider this to be the zone of therapeutic value.
2. At depths greater than 2.4 cm there is a rapid decline in intensity to the depth of maximum penetration of the electrons. At greater depths, the percentage depth dose due to X rays is about 1 per cent.
3. Since the number of electrons per gram is approximately the same for most body substances such as bone, muscle and fat, the absorption in ergs per gram will not vary within these tissues.
4. The limited penetration of the beam results in integral doses which are small compared with those arising in X-ray or radium therapy.

The dose distributions for electrons and X rays are so dissimilar that it is difficult to compare integral dose values. However, taking 80 per cent as the limit of effective treatment, the 80 per cent isodose surface is at the same depth for 140 kV X rays (0.25 mm Cu + 1 mm Al filter, 8 mm Al H.V.L.) as for 8 MeV electrons. For radium therapy, the calculations of Bush (1946) have been used to find the integral dose from a two-plane implant (with 2.5 cm separation) of the chest wall after mastectomy. Integral dose values for a treated area of 100 cm² are, roughly:
- Electron therapy: 0.3 Mgm-rads per 1,000 rads at the peak.
- X-ray therapy: 1.4 Mgm-rads per 1,000 rads on the skin.
- Radium implant: 1.6 Mgm-rads per 1,000 rads.
Electron therapy is therefore likely to cause less systemic upset than X-ray or radium therapy in the treatment of extensive diseases involving the skin and subcutaneous tissues.

CLINICAL APPLICATIONS

As the depth dose falls to 80 per cent of the maximum dose at 2.4 cm below the skin surface, it was felt that this was about the maximum thickness of tissue that could be adequately treated. The diseases favourably situated for treatment by electrons of this energy are therefore those which...
Electron Therapy at 8 MeV

Electron therapy is especially valuable when it can be used as an alternative to a large radium mould. Besides giving a more uniform irradiation over the first 2.4 cm below the surface, it avoids the considerable irradiation of the staff which inevitably occurs during the handling of large moulds.

Examples of cases which have been treated:

Case 1. N.B. Fungating glands of neck (Figs. 9 and 10)

Two years previously the patient had a wedge excision of the left pinna for a squamous cell carcinoma. Six weeks after the operation an enlarged node developed behind the angle of the left jaw. This was treated by a 7 c telecobalt unit supplemented by a radon seed implant. There was some regression, but 18 months later when the patient next reported, a raised fungating tumour 6 cm diameter was present over the mastoid region and there were also several enlarged nodes 2 cm in diameter below the area of ulceration. A biopsy showed the presence of squamous cell carcinoma. The ulcerated lesion and the nodes were treated by electron therapy; a surface dose of 5,400 rads was given in 22 days to a field area of 91 cm². After treatment the skin underwent moist desquamation which took one month to subside. The ulcerated area gradually healed over and the lymph nodes disappeared. Seven months later there was no recurrence and the treated area was satisfactory.

Case 2. J.P. Extensive rodent ulcer of skull and orbit

This patient attended with a very large rodent ulcer which had been present for 22 years. It had been treated ten years previously by a β-ray plaque and diathermy. The ulcer, which measured 15 x 12 cm, involved the region of the left orbit and extended to the nose and the temporal region of the scalp. Electron therapy was given, using a special mask to include the tumour and 1 cm of normal surrounding skin. A maximum dose of 6,000 rads in 29 days was given. After the treatment, a patchy moist reaction developed on the skin which took about six weeks to subside. The ulcerated area is healing slowly and several bone sequestra have separated from the deeper part of the orbit.

Case 3. J.C. Recurrent skin nodules from carcinoma breast

Four years previously the patient had a radical mastectomy followed by radiotherapy for a carcinoma of the right breast. Three months previously the patient developed a recurrence on the right chest wall which measured 8 x 5 cm and was ulcerated over an area 3 cm in diameter. It was probably less than 3 cm thick and was treated by electron therapy, a dose of 6,000 rads being given in 28 days to a 12 cm field. Following the treatment the patient developed moist desquamation of the skin which took one month to subside. Four months after treatment there is no sign of recurrence and the area of ulceration has almost healed.
Case 4. E.I. Carcinoma buccal aspect of cheek
(Figs. 11, 12 and 13)

The patient had noticed a swelling in the right cheek for four months. On the buccal aspect of the cheek there was a solid infiltrating tumour 4.5 cm in diameter which extended from the upper alveo-buccal sulcus to the lower alveolus and spread forwards almost to the angle of the mouth. Histologically, it was a squamous carcinoma. The maximum depth of the tumour from the skin surface was 2-6 cm. Treatment was given by electron therapy, a peak dose of 5,500 rads being given in 28 days through an oval field (7 x 5 cm) using a lead mask. The treated skin showed a dry desquamation. An epithelial reaction which appeared on the mucosa of the cheek during the third week of treatment persisted for about one month. The tumour regressed satisfactorily and three months later the patient is well.

The number of patients that have been treated is small, and it is too early to form an opinion of the value of 8 MeV electron therapy or to compare it with other methods of treatment. The skin and mucosal reactions in areas which have not been previously irradiated have been comparable to those observed with the same doses of γ radiation. The excellent response which has been observed in some of the tumours has encouraged us to continue to use this treatment for a small number of selected tumours.

ACKNOWLEDGMENTS

We are indebted to Mr. G. F. S. Harding who has made many of the alterations to the machine that were needed, and who has assisted with most of the measurements and experimental work. We would also like to thank Mr. G. R. Newbery and Dr. C. A. P. Wood for their interest in this work. A. Batchelor is now a member of the M.R.C. Radiobiological Research Unit, A.E.R.E., Harwell.

SUMMARY

The use of an 8 MeV linear accelerator for the treatment of patients with electrons is described. Dose distributions in water show a zone extending from the surface to a depth of 2-4 cm in which the irradiation is uniform to within 20 per cent, with a steep decline at greater depths. It is considered that effective treatment can be given only to a depth of 2-4 cm. The types of case which can be treated with 8 MeV electrons are discussed and a few treatments which have been given are described.

REFERENCES