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IONIZATION CHAMBER DOSIMETRY

IONIZATION CHAMBER DOSIMETRY FOR HIGH ENERGY
PHOTON AND ELECTRON BEAMS:
AN EXPERIMENTAL STUDY

By

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A Report

(Industrial Project)

Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree
Master of Engineering

McMaster University

September 1978

MASTER OF ENGINEERING (1978)
(Engineering Physics)

McMASTER UNIVERSITY
Hamilton, Ontario

TITLE: Ionization Chamber Dosimetry for High Energy
Photon and Electron Beams: An Experimental
Study

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NUMBER OF PAGES: ix, 85

Part B

ABSTRACT

A number of recently published papers have been critical of the values of C_E and C_λ by the ICRU as absorbed dose conversion factors for ionization chambers used in electron or photon beams.

This report examines the subject in light of these recent works. Presented is a review of both theoretical and experimental results published to date along with the results of experimental work carried out at this facility. The present study concentrated on the measurement of the absorbed dose conversion factors for electrons and 25 MV photons. It also attempted to determine how the conversion factors might be influenced by such factors as chamber design buildup cap thickness and composition, and phantom composition.

Measurements were made using electrons with 10 to 32 MeV initial energy and a 25 MeV photon beam, all produced by a Sagittaire Model Therac 40 linear accelerator. Checks on the stability of the measurement system were made using a ^{60}Co source. Fricke ferrous sulfate dosimetry was used for absorbed dose measurement in the determination of C_E .

The results of the study would indicate that there

is little or no effect on the measured values of C_E or C_λ introduced by either the sleeves or phantoms for the radiation qualities studied. The results of the absorbed dose conversion factor study would indicate that the values recommended by the ICRU are sufficiently accurate for use in most instances. The data would tend to support the argument that if there is an error in one of the ICRU derivations, the error in theory lies in the C_E determination rather than that for C_λ .

ACKNOWLEDGEMENTS

I would like to acknowledge the supervision and assistance of Dr. D.V. Cormack throughout this project. I would like to thank Helen Boese for her valuable assistance in conducting the experiments and Drs. A.F. Holloway and A.M. Sourkes for their continuing interest and valuable discussion throughout these studies.

I would also like to thank Mr. E. Cartwright and Mr. J. Legal and the staff of the electronic and machine shops for their excellent technical support throughout the project.

Finally, I would like to acknowledge financial support of the Manitoba Cancer Treatment and Research Foundation, at which these studies were conducted.

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1. INTRODUCTION

1.1 The Absorbed Dose and Its Determination

A quantity of primary interest in radiation therapy and radiobiology is the absorbed dose* in a particular biological material. Since this quantity is a measurement of the energy imparted, the effects of a given quality radiation on the biological material is normally expressed as a function of the absorbed dose. Thus one can easily see the importance of adequate dosimetry when radiation is used for either therapy or experimental purposes.

Accurate determination of the absorbed dose, however, is not a simple task. Its absolute measurement or calculation for each case of interest would prove to be not only impractical but in many instances impossible. Therefore, what is required is some sort of standard to which the individual cases may easily be compared.

For absorbed dose standardization, it is necessary to choose a well-defined and readily available material and to choose standard conditions under which the absorbed dose

* ICRU 19 (1971) defines the absorbed dose, D, as the ratio of the mean energy imparted by ionizing radiation to matter, $d\bar{\epsilon}$, to the mass of the matter, dm , in a volume element. The special unit for the absorbed dose is the rad where

$$1 \text{ rad} = 10^{-2} \text{ J kg}^{-1}.$$

should be measured (ICRU 1969). This in itself is not a simple task since the absorbed dose calibration is influenced by such factors as the energy-fluence distribution of the incident radiation, the depth of the point of measurement, the area of the incident beam and the dimensions of the irradiated material.

Standardization with respect to the irradiated material and the last three of the points mentioned above is achieved to some degree through recommendations of the ICRU (1969, 1972). They have recommended the use of a water phantom of specified dimensions along with specified beam size and source-to-surface-distance (SSD). This, however, still leaves the problem of energy-fluence distribution which is a function of the radiation source employed in each case.

A more serious problem is the fact that it is not normally possible to make absorbed dose measurements in water directly. Rather, one must make the measurements using some reference material and then relate this to the dose in water if the reference probe had not been there. Normally probes employing either ionization, chemical, calorimetric, photographic emulsion, or solid state principles are employed. Before any of these methods may be used in making absorbed dose measurements in a given clinical or experimental situation, they must first be calibrated in terms of a standard radiation source at a national or

international reference lab.

In addition, each of the above methods will have certain associated advantages and disadvantages which will affect the applicability of its use in routine dosimetry. For example, calorimetry, which is the most direct method for determination of the absorbed dose, requires the use of very difficult and complex techniques and equipment thus making it an unsuitable technique for use in day-to-day dosimetry (Laughin and Genna 1966). Chemical dosimetry*, while being simpler than calorimetry, still requires techniques and equipment and rather large doses which limit its routine use (Fricke and Hart 1966). The use of photographic emulsions (Dudley 1966) provides quick and relatively simple dosimetry but the techniques often lacks the degree of accuracy required in many cases. This lack of accuracy is also the problem faced by solid-state methods (Fowler and Attix 1966, Fowler 1966).

1.2 Determination of Absorbed Dose by Ionization Methods

The system for measuring the absorbed dose which is normally employed in routine dosimetry is that using ionization chambers (Boag 1966). Its popularity lies in its

*For details of chemical dosimetry methods see Chapter 3.

ability to provide reasonably precise absorbed dose determinations quickly and simply without the need for complicated techniques and elaborate equipment. Ionization chambers are also readily available commercially in a variety of standard types and sizes and are suitable for calibration at a standard laboratory.

This is not to say that the determination of the absorbed dose using ionization chambers is a straightforward and trouble-free method. There is in fact one major problem which plagues the use of this technique. This lies in the fact that there presently does not exist an absorbed dose standard for use in the calibration of ionization chambers (Greene and Massey 1977). At present national standardizing laboratories are only able to calibrate ionization chambers in terms of exposure* by comparison with exposure standards used with a well known radiation source such as ^{60}Co gamma rays or 2 MV photons (Henry 1976, 1978)#. It is therefore necessary to determine the absorbed dose indirectly through the use of the exposure calibration.

* ICRU 19 (1971) defines the exposure, X, as the quotient dQ by dm where dQ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons (or positrons) liberated by photons in a volume element of air having mass dm are completely stopped in air. The unit of exposure is the roentgen (R) where:

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C kg}^{-1} \text{ (exactly)}$$

The exception to this is the absorbed dose calibration for Cobalt 60 provided by the National Research Council, Ottawa.

This is done by exposing the ionization chamber to the incident radiation at the point where one wishes to know the absorbed dose. The result is a meter reading, M , for the system* previously calibrated for exposure. M is corrected for variations due to temperature and pressure (ie. density of the air) and for lack of saturation of charge in the chamber (See Chapter 4). The absorbed dose at the point is then given by:

$$D = M N_c C \quad \text{Eqn. 1.)}$$

where N_c is the exposure calibration factor for the ionization chamber at the calibration quality (ex. ^{60}Co), and C is the absorbed dose conversion factor appropriate to measurements made in a phantom irradiated with the incident radiation in question.

Since both M and N_c may be measured reasonably accurately, it follows that the accuracy with which one is able to measure the absorbed dose using an ionization chamber is related to the accuracy with which the conversion factor, C , may be determined. Therefore a great deal of theoretical, along with some experimental work has been carried out with the aim of producing a complete set of conversion factors for use with all radiations of clinical interest. This has resulted in the International Commission on Radiation Units

* The system, in the present context, refers to a thimble ionization chamber along with the electronics necessary to obtain a meter reading proportional to the exposure at a well defined point.

and Measurements (ICRU) publishing recommended values for use with electron (ICRU 1972) and photon (ICRU 1969) beams.

Almost since the time of their original release, however, these reports have come under fire from a number of authors on the basis of various theoretical calculations (See Section 2.3). Pointing out that various aspects of the ICRU derivations of the conversion factors appear to be inconsistent, each of these authors has put forward a new "correct" derivation resulting in slightly different factors being produced.

Unfortunately, nearly all of this work has been completely of a theoretical nature with little or no attempt being made at an experimental testing of the theories. In fact, even the ICRU reports themselves contain very little experimental backing for the recommended conversion factors.

These facts in mind, the present study was undertaken in the hope of providing experimental information which might hopefully help to resolve the current controversy sparked by these theoretical works. Because of constraints placed by the availability of radiation sources, the study focussed primarily on the investigation of the conversion factors for high energy electron beams and 25 MV X-rays.

The results of these investigations are presented in Chapter 6. Chapter 2 deals with the theoretical determination of the absorbed dose conversion factors with a brief review of some of the recent publications critical

of the ICRU reports. The measurement of the absorbed dose required for the experimental determination of the C factors was accomplished through the use of the ferrous sulfate method of chemical dosimetry. Chapter 3 describes in detail the system used for these measurements. Chapter 4 discusses the various aspects of the use of ionization chambers in the measurement of absorbed dose while Chapter 5 describes the experiments in which the absorbed dose conversion factors were measured. After the results of these are presented in Chapter 6, a short chapter presents the basic conclusions of this report.

2. THEORY

2.1 C_λ ; The Absorbed Dose Conversion Factor for Photons

The theoretical basis for the use of ionization chambers in the determination of the absorbed dose at a point in water lies in that the Bragg-Gray (Gray 1937) theory is valid for each case in which the method is used. The application of the Bragg-Gray principle and its use in the theoretical determination of the absorbed dose conversion factor for photons, C_λ , is treated in detail in ICRU Report 14 (1969). Therefore only a brief description will be given here.

The basis for the use of the theory is that the absorbed dose, D , in an irradiated medium in the immediate vicinity of a small gas-filled cavity may be determined from the ionization in the cavity by the Bragg-Gray equation:

$$D = J (\bar{W}/e) \bar{S}_{mg} \quad \text{Eqn. 2.})$$

where J is the quotient of the ionization charge by the mass of the gas, \bar{W} is the average energy expended by the electrons in the gas per ion pair formed, e is the charge on the electron, and \bar{S}_{mg} is a weighted mean ratio of the mass stopping power of the medium to that of the gas for the electrons crossing the cavity (ICRU 1969). Since \bar{W} and e are physical constants and \bar{S}_{mg} can, in principle be determined from theory,

the use of Bragg-Gray theory requires the determination of J . While this might appear to simply require the calculation of the charge induced in the cavity, the situation is complicated by the fact that it is not normally possible to determine the mass of the gas to the desired degree of accuracy. Thus it is necessary to rely on a method which does not require a direct knowledge of the absolute mass.

To do this one proceeds indirectly by first determining the exposure for a standard radiation such as ^{60}Co or 2MV X-rays. One knows that for a given meter reading the exposure at a point in a water phantom, X_w^* , would be given by:

$$X_w = M N_c d \quad \text{Eqn. 3.)}$$

where M is the meter reading corrected for temperature and pressure and the lack of saturation of charge, N_c is the exposure calibration factor from a national standards laboratory, and d is a factor to account for the displacement of water by the cavity.

Now for photons of this energy, the kerma[#], K_w , at a point in water which receives X_w is related to the

* Strictly speaking, the exposure is given only for a point in air and one is not in fact actually measuring the exposure at a point in water unless the chamber is specifically calibrated in water. In practice this quantity is referred to as either the apparent exposure or simply the exposure in water.

ICRU 19 (1971) defines the kerma, K , as the quotient of dE by dm , where dE is the sum of the initial kinetic energies of all charged particles liberated by indirectly ionizing particles in a volume element of the specified material and dm is the mass of the matter in that volume element. The unit of the kerma is the rad.

exposure by:

$$K_w = X_w \frac{(\overline{\mu_k/\rho})_w}{(\overline{\mu_{en}/\rho})_a} (\bar{W}/e) \quad \text{Eqn. 4.}$$

where $(\overline{\mu_k/\rho})_w$ is the average value of the mass energy-transfer for water and $(\overline{\mu_{en}/\rho})_a$ is the average value of the mass energy-absorption coefficient for air.

For points in water beyond the maximum of the build-up curve, the absorbed dose is directly proportional to the kerma, approximately independent of the depth at the point of measurement. Thus we now have a direct relationship between the exposure and the absorbed dose at the point of measurement for the calibration energy (^{60}Co or 2MV). This is given by:

$$\begin{aligned} D_w &= b X_w \frac{(\overline{\mu_k/\rho})_w}{(\overline{\mu_{en}/\rho})_a} (\bar{W}/e) \\ &= M N_c (C)_c \end{aligned} \quad \text{Eqn. 5a.}$$

where

$$(C)_c = A (\bar{W}/e) \frac{(\overline{\mu_k/\rho})_w}{(\overline{\mu_{en}/\rho})_a} \quad \text{Eqn. 5b.}$$

is the conversion factor for finding the absorbed dose from the exposure meter reading when used at the calibration energy c . The constant A is the proportionality factor accounting for displacement and the kerma-to-absorbed dose ratio.

Now if one assumes that the ionization chamber will still behave as a Bragg-Gray cavity at radiation qualities other than the one at which it was calibrated,

one can proceed to determine the conversion factors for these energies. One eliminates the need of having a knowledge of the mass of the cavity gas by expressing things in terms of J/M , that is the charge-mass quotient as a ratio of the meter reading as determined at the calibration energy.

If both of these steps are valid, then the dose at a point in water due to a beam of radiation of quality λ is given by:

$$(D_w)_\lambda = M N_c C_\lambda \quad \text{Eqn. 6.)}$$

The conversion factor C is now given by:

$$\begin{aligned} C_\lambda &= (C_\lambda)_c \frac{(\bar{S}_{wg})_\lambda}{(\bar{S}_{wg})_c} \frac{p_\lambda}{p_c} \\ &= A (\bar{W}/e) \frac{(\overline{\mu}_w/\rho)_w}{(\overline{\mu}_{en}/\rho)_a} \frac{(\bar{S}_{wg})_\lambda}{(\bar{S}_{wg})_c} \frac{p_\lambda}{p_c} \quad \text{Eqn. 7.)} \end{aligned}$$

where (\bar{S}_{wg}) and $(\bar{S}_{wg})_c$ are the average values of the mass stopping power ratios of water relative to air at the qualities λ and c respectively and p_λ and p_c are the factors to account for the perturbation of the field by the cavity for the radiations λ and c .

Thus in Eqn. 7 we have an expression making it possible to calculate values of C_λ , the absorbed dose conversion factor for photon beams of any quality for which the Bragg-Gray principle may be assumed to hold. Using this expression and calculated stopping power data, values of C_λ for energies up to 35 MeV have been calculated and

tabulated in ICRU Report 14 (1969).

2.2 C_E ; The Absorbed Dose Conversion Factor for Electrons

We may derive an expression for the electron absorbed dose conversion factor, C_E , in much the same way as was done for the derivation of C_λ . We again start by applying the Bragg-Gray relation, this time including an extra factor, p , to account for the fact that the Bragg-Gray condition of undisturbed particle fluence is not met completely in the case of electrons. The relation is:

$$D = J (\bar{W}/e) \bar{S}_{mg} p_{mg} \quad \text{Eqn. 8.})$$

where the notation of Eqn. 2 applies.

Once again it is possible to eliminate J with a number proportional to the meter reading of an exposure meter calibrated with a reference photon beam such as ^{60}Co or 2 MV X-rays. For the case of electrons:

$$J = A M N_c \quad \text{Eqn. 9.})$$

Thus we may express the absorbed dose at a point in a water phantom in terms of the meter reading on a calibrated exposure meter as:

$$\begin{aligned} D &= M N_c A (\bar{W}/e) \bar{S}_{mg} p_{mg} \\ &= M N_c C_E \quad \text{Eqn. 10.}) \end{aligned}$$

where the absorbed dose conversion factor is given by:

$$C_E = A (\bar{W}/e) \bar{S}_{mg} P_{mg} \quad \text{Eqn. 11.})$$

Thus we again have an expression from which it is possible to calculate the conversion factors for various quality electron beams. This has been done for beams as a function of electron energy and depth of measurement in the phantom and the results tabulated in ICRU Report 21 (1972). This report should also be consulted for a more detailed derivation of C_E along with the various factors which might affect its calculation such as the problem of the secondary electron spectrum or that of uncertainties in the stopping power ratios.

2.3 Recent Theoretical Work

As was mentioned in the Introduction, papers critical of the ICRU derivations of C_λ and C_E began to appear in the literature soon after the publication of the recommended values. Some critics suggested that it was not strictly possible to apply the Bragg-Gray principle to a commercial ionization chamber under most conditions. Others claimed that since both are meant for use in a water phantom, the assumption of a water-equivalent walled chamber in the derivation of C_λ and of an air-equivalent walled for the derivation of C_E presents a major inconsistency.

The controversy came to a head in 1976 when Nahum and Greening presented what they said to be a clear inconsistency in the derivations of C_λ and C_E . They pointed out that according to present knowledge of the secondary electron spectrum from an incident photon beam and of electron transport in a medium, if one observed the electron spectrum at a depth of 3 cm in a water phantom that came about as a result of firstly an incident beam of 35 MeV photons and secondly of a beam of 10 MeV electrons, the spectrum should be the same in both cases. That is, they said that in both cases there should be a secondary electron spectrum with a mean energy of 4 MeV. Furthermore, the same electron spectrum should result in the same absorbed dose at that point and in the same reading for a calibrated exposure meter inserted at that point. This being the case, it follows that the value of C_λ as derived from Eqn. 7 for 35 MeV photons and the value of C_E from Eqn. 11 for 10 MeV electrons at a depth of 3 cm should be equal. The values tabulated in ICRU 14 (1969) and ICRU 21 (1972), however, differ by approximately 4%.

Nahum and Greening blamed this discrepancy on a poor understanding of how the chamber was measuring exposure (1976) and on errors in the stopping power data used in the derivation of C_λ (1977). After publication of their 1976 work, a number of authors presented various other explanations for the discrepancy between C_λ and C_E . In each case the

authors presented somewhat different arguments to explain the discrepancy. Unfortunately most of the papers have been rather short with very few details of as to how the authors reached their conclusions. Therefore, rather than reviewing each of the various arguments in detail, a list of those which have appeared in the literature is presented in Table I. Along with each reference is included the derivation which the authors blamed the discrepancy on, i.e. that for C_{λ} or C_E , along with the reasons for doing so.

Besides giving very few details of the work, most of the recent papers concerning C_{λ} and C_E were mainly of a theoretical nature, usually making no attempt at obtaining experimental support for the ideas presented. The only exceptions to this are papers by Kutcher et al. (1977), Pitchford and Bidmead (1978), and Almond and Svensson (1977) which provide detailed descriptions of their theoretical calculations and/or experimental tests of their theories. The later of these, that due to Almond and Svensson, is worth reviewing in greater detail.

The basic argument of this work is that the assumption of ICRU 14 (1969) of a water-equivalent walled chamber and of ICRU 21 (1972) of an air-equivalent wall are too restrictive for proper application to commercial ionization chambers used with photon or electron beams over large quality ranges. They say that variations in the conversion factors will come about as a result of what

Table I
Recent Publications Critical of ICRU Derivations
of C_λ and C_E

| Reference | Derivation at Fault | Reasons |
|---|---------------------|--|
| Greene and Massey (1978) | Neither | C_E and C_λ correct to required accuracy |
| Franz (1971) | C_λ | ICRU 14 wrong in assuming water-walled Bragg-Gray cavity |
| Nahum and Greening (1976), (1977) Nahum (1978) | C_λ | Poor understanding of detection mechanism, wrong stopping power ratios |
| Kutcher et al. (1977) | C_λ | Effect of wall and cap not properly accounted for |
| Pitchford and Bidmead (1978) | C_λ | Wrong in assuming water-walled Bragg-Gray cavity |
| Matsuzawa et al. (1974) | C_E | Improper to assume air-walled Bragg-Gray cavity when using lucite cap |
| Holt and Kessarlis (1977) | C_E | Incomplete definition of C_E |
| Williams (1977) | C_E | Incomplete definition of C_E |
| Fregene (1977) | Both | Inadequate solid cavity theory |
| Almond and Svensson (1977) | Both | ICRU definitions too restrictive for use with real chambers |
| Shiragai (1978) | Both | Present definitions do not account for wall material |

proportion of the electron flux reaching the chamber was generated in the phantom material, buildup cap, and chamber wall. The value of C to be used will depend on the relative proportions due to each of these components. It can also be seen that the material of which the cap and wall are made should play some role in determining these proportions.

They also conducted a number of experiments aimed at measuring the effects of wall and cap material for use with a ^{60}Co calibration source. The results of these studies tend to support their theory, indicating that the material used may affect the value of C_λ by up to 3% even for use with a low energy calibration source such as ^{60}Co .

Despite the advances made by studies such as that described by Almond and Svensson, Table I clearly indicates that the situation concerning the theoretical derivations of C_λ and C_E remains very confused. It is clear that much more work needs to be done, especially of an experimental nature, investigating the effects of buildup caps, wall materials, etc. for various quality radiations.

3. CHEMICAL DOSIMETRY

In the experimental determination of absorbed dose conversion factors for ionization chambers it is necessary to employ a dosimetry system which will provide an accurate determination of the absorbed dose at the point in the water phantom for which the ionization chamber produced a meter reading. That is, by rearranging Eqn. 1 we see that the conversion factor is determined experimentally by:

$$C = D / (M N_c) \quad \text{Eqn. 12.})$$

Thus the accuracy with which one may measure C is directly proportional to the accuracy with which D may be measured.

There are two types of dosimetry which are able to provide the level of accuracy required in these measurements. The first, calorimetry, while providing precise and reproducible results, is too complex for use in a series of experiments where a large number of measurements must be made (Laughlin and Genna 1966). Therefore, the second type, chemical dosimetry, was employed for absorbed dose determination in these experiments.

Because of the importance of the role played by the dosimetry system in the measurement of the conversion factors, the remainder of this chapter will deal exclusively with the description of the chemical dosimetry system used.

3.1 Ferrous Sulfate Dosimetry

Of the various chemical dosimetry systems available, the ferrous sulfate or Fricke dosimeter system is generally recognized as being the most suitable with respect to precision, reproducibility, and linearity of response (ICRU 1969, Fricke and Hart 1966). On the basis of the extensive studies which have been carried out investigating the response of this system to different qualities of ionizing radiation, it can now be said to be well understood and suitable for use in the precision measurement of absorbed dose or for absorbed dose standardization.

The Fricke system has a number of features which make it particularly suitable for dosimetry: 1) it requires standard, relatively simple equipment for analysis; 2) the system dose response is independent of dose rate up to about 10^8 rads/sec; 3) the conversion factor used in determining the absorbed dose in water from the absorbed dose in the dosimeter solution is close to unity and nearly independent of radiation quality for qualities used in radiotherapy; 4) it is possible to have both the dosimeter solution and its container have nearly the same linear attenuation coefficients as water, thus reducing the perturbation to the radiation field introduced by the dosimeter. The principle disadvantage of the system is its low sensitivity, requiring an absorbed dose of the order of a few kilorads in order to obtain a precision of 1%.

The Fricke dosimeter is based on the oxidation of an aerated ferrous sulfate solution (Fricke and Hart 1966). Through a well understood mechanism, ferrous ions, (Fe^{2+}), are oxidized to form ferric ions, (Fe^{3+}). As long as enough oxygen is present in the solution during the irradiation, the final ferric ion concentration is directly proportional to the energy absorbed, which in turn is directly proportional to the absorbed dose. Thus a determination of the number of ferrous ions oxidized may be used in determining the absorbed dose in the solution.

The most convenient method for the determination of the final ferric ion concentration is the use of absorption spectroscopy which provides a fast, accurate method for the analysis of low ferric ion concentrations even with quantities of dosimeter solution of the order of a few ml. Ferric ions have absorption maxima at 224 and 304 nm wavelengths. Thus the analysis is readily accomplished by direct spectrophotometry of the ferric ions at one of these wavelengths.

Although the sensitivity of the ferrous sulfate dosimeter is approximately doubled when measurements are made at 224 nm in comparison to when they are made at 304 nm, the normal procedure is to operate at the later wavelength. This is because impurities from the plastic containers used during irradiation tend to be more troublesome at 224 nm. (ICRU 1969).

In practice one determines the absorbed dose in the

solution by first measuring the difference in the optical density at 304 nm between an irradiated solution and an unirradiated control, ΔOD . The absorbed dose in rads is then determined according to the formula:

$$D = \frac{N_A \Delta OD 100}{\epsilon_m 10^3 G f \rho l C_T} \quad \text{Eqn. 13.}$$

where N_A = Avagradro constant

$$= 6.02 \times 10^{23} \text{ molecules/mole}$$

ϵ_m = molar extinction coefficient for ferric ions

$$= 2205 \pm 3 \text{ litre mole}^{-1} \text{ cm}^{-1} \text{ for } 0.8 \text{ N (} 0.4 \text{ mole/litre) H}_2\text{SO}_4 \text{ dosimeter solution @ } 25^\circ\text{C}$$

G = N/E_D , where N is the number of ferric ions produced by the energy, E_D , imparted to the solution. (The numerical value of G is normally given as the number per 100 eV.)

$$f = 6.24 \times 10^{13} \text{ eV/rad}$$

ρ = density of irradiated solution

$$= 1.024 \text{ for } 0.8 \text{ N H}_2\text{SO}_4 \text{ solution}$$

l = optical path length in cm

C_T = temperature correction factor

$$= \frac{1}{(1-0.0015(t-t'))(1-0.007(t-t'))}$$

$$t = 25^\circ\text{C}$$

t' = irradiation temperature

t'' = analysis temperature

100 and 10^3 are conversion factors for G and ϵ_m to maintain consistant units.

Now for the 0.8 N H_2SO_4 solution and 1 cm absorption cell used in the present experiments, Eqn. 13 reduces to:

$$D = 4.275 \times 10^5 (\Delta OD/G) \quad \text{Eqn. 14.}$$

The measurement of the G factor in Eqns. 13 and 14 has been the subject of a number of studies, the results of which have been tabulated. The recommended values for use with 0.8 N H₂SO₄ solution are:

$$\begin{aligned} 15.5 \pm 0.2 / 100 \text{ eV for } ^{60}\text{Co}, \\ 15.7 \pm 0.6 / 100 \text{ eV for 11 to 30 MV photons,} \\ 15.7 \pm 0.6 / 100 \text{ eV for 1 to 30 MeV electrons} \end{aligned}$$

(ICRU 1969, 1972).

The standard solution for Fricke dosimetry consists of 0.001 M ferrous sulfate, FeSO₄, (or ferrous ammonium sulfate, Fe(NH₄)₂(SO₄)₂) and 0.8 N aerated sulfuric acid, H₂SO₄. Normally 0.001 M sodium chloride, NaCl, is included. The NaCl desensitizes the system to organic impurities which compete with the oxidization reaction in converting the ferrous ions (Fricke and Hart 1966).

Fricke and Hart caution against the addition of NaCl if the dosimeter is to be used with high dose rate pulsed electron beams. The reason is that it imparts a more pronounced dose rate dependence to the dosimeter. Since the Sagittaire linear accelerator used in these studies produces a pulsed electron beam it was decided to investigate the effect of NaCl on the system. Ferrous sulfate dosimeters, with and without salt, were compared for each of the electron energies to be studied along with 25 MV photons and ⁶⁰Co gamma rays. All comparisons were carried out at the

200 MU/min* dose rate used throughout the remainder of the studies. This study showed no detectable difference in the salt:no-salt ratio for the pulsed high energy electrons and the continuous ^{60}Co beam. The conclusion was that at this dose rate the salt solution was unaffected by the pulsed nature of the beam. Therefore solution containing NaCl was used throughout the studies.

3.2 Irradiation System

As stated, the dosimeter solution employed in these studies was the Fricke dosimeter with NaCl. The solution was normally prepared in one litre quantities and stored at a temperature below 10 C before being used. Solution was stored for a maximum of four weeks before use.

The dosimeter was irradiated in disposable polystyrene tubes# measuring 75 mm long by 12 mm diameter with a 1 mm thick wall. The tubes are equipped with polystyrene caps which provide a water tight seal. Unopened tubes are guaranteed sterile by the manufacture.

Tubes were filled no more than three hours before irradiation with approximately 5.25 ml of dosimeter. Filling

* MU/min = monitor unit per minute, where 1 MU is approximately equal to 1 rad.

2054 Tube, Falcon Plastics, 1950 William Drive, Oxnard, California, USA.

was accomplished using disposable pipettes. Care was taken to ensure no contamination of the solution occurred as a result of filling.

The effect of the time the dosimeter was stored in the tube was investigated by irradiating samples stored for various lengths of time before irradiation. The effect of the time the solution was left in the tubes between irradiation and analysis on the spectrophotometer was also investigated. In both cases, periods of up to four hours showed no observable effects. To eliminate any possible risk of a storage effect undetected by this study, however, analysis was always carried out within two hours of completion of the irradiations and any tubes which had been filled more than five hours before they were to be irradiated were discarded and replaced with freshly filled ones.

The apparatus used and the conditions under which the irradiations were carried out will be described in detail in Sections 5.2 and 5.3. The dosimeters were irradiated in a 20 x 20 cm radiation field to ensure that they were entirely within the beam. During irradiations the tubes containing the dosimeter solution were centered at a depth of 3 cm in the water phantom or at an equivalent depth of 3.0 gm/cm^2 of lucite*. The only exception to this was a number of runs using 10 MeV electrons carried out at a

* Trade name for polymethyl methacrylate. Also known as Perspex, Plexiglass, etc.

depth of 2.5 gm/cm^2 .

While conducting the experiments, there was some concern expressed as to the possibility that the size of the tubes used for holding the dosimeter might have some effect on the measured absorbed dose. While the size proved to be convenient in terms of the volume of the solution available for analysis, it was felt that the dose might not be uniform over the volume of solution. The concern was for both along the length of the tube and across its diameter.

The question of uneven dose distributions along the 7.5 cm length of the tubes was dispelled by consulting the profiles of the beam for the various radiation qualities which are regularly compiled as part of the routine checks of the equipment used in radiotherapy (Boese 1978). These profiles are compiled using at various times; ionization chambers, Fricke dosimeters, and photographic plates with the majority employing the photographic method. Tests were carried out on a weekly basis throughout the four months during which the experiments were conducted. The profiles compiled for the radiation qualities of interest to this study showed no observable variation in the absorbed dose along the length of the tubes.

Since the absorbed dose conversion factor for electrons varies with depth of measurement it is important in the experimental determination of this factor that one is able to measure the absorbed dose at a well defined

point. Therefore it was important to determine what effect, if any, the finite diameter of the dosimeter tube would have on measuring the absorbed dose at the point at the center of the tube. Since the diameter of the tube was such that for energies such as 10 MeV it covered a significant section of the depth-dose curve, this presented a major concern.

The effect of the tube diameter was determined by calculating the weighted mean of the absorbed dose in the dosimeter solution and comparing it with the expected absorbed dose at the point at the center of the tube. The weighting factor used was the cross sectional area of the dosimeter solution perpendicular to the beam at a given depth. Absorbed dose values for calculating the mean and the value at the center of the tube were taken from depth-dose curves in Figure 1. For the more critical problem of 10 MeV electrons with a sharply peaked depth-dose curve, the absorbed dose data was taken from Figure 2. In each case the weighted mean was calculated using eleven points across the diameter of the tube in the direction parallel to the beam. Calculations were carried out for a tube centered at a depth of 3.0 cm with the exception of the 10 MeV case where it was also done for 2.0 and 2.5 cm depths.

The calculations showed no apparent difference between the weighted mean value of the absorbed dose throughout the tube and the absorbed dose at the center point for

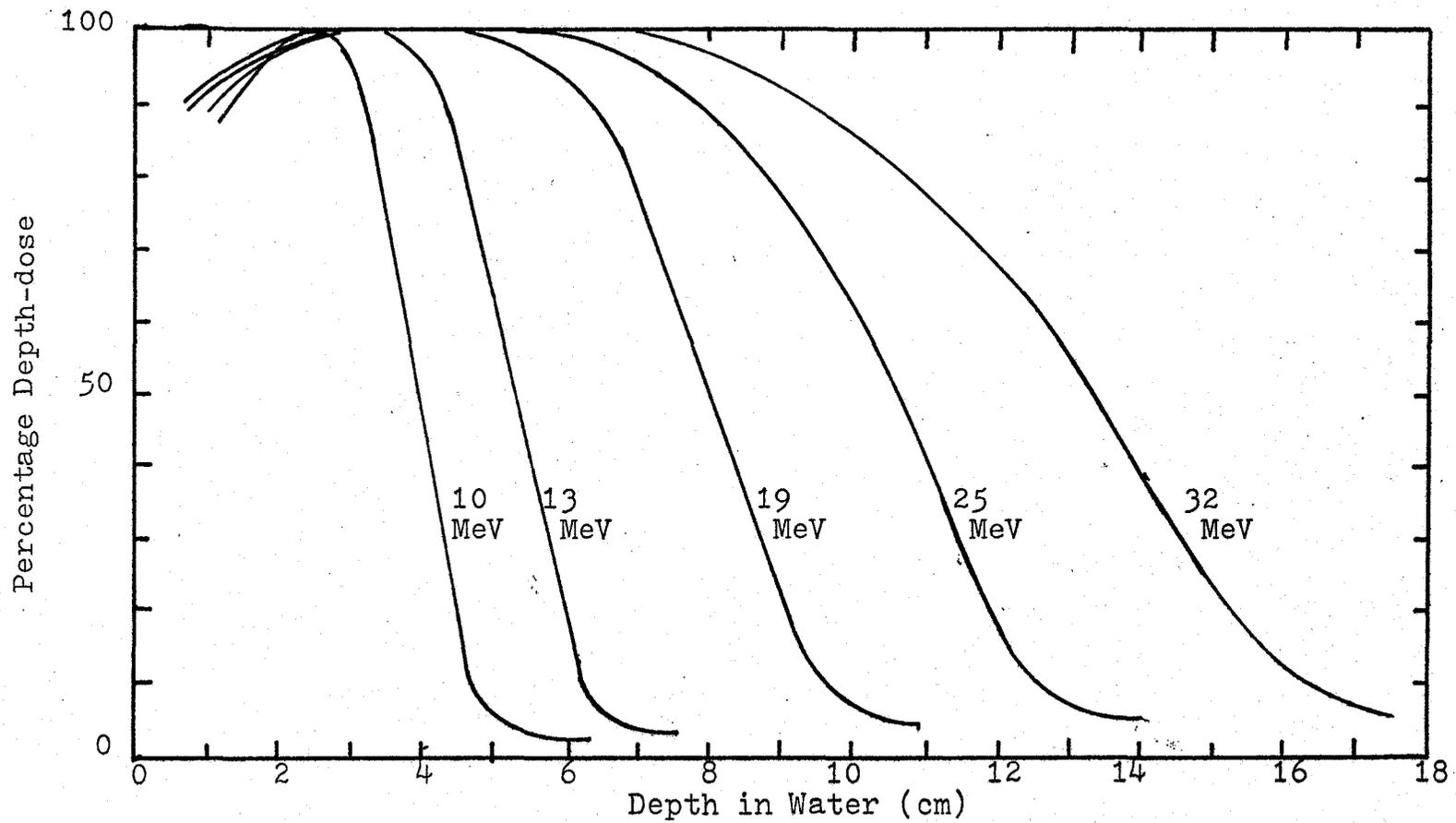


Figure 1. Depth-dose curves for Sagittaire linear accelerator (from AECL 1974).

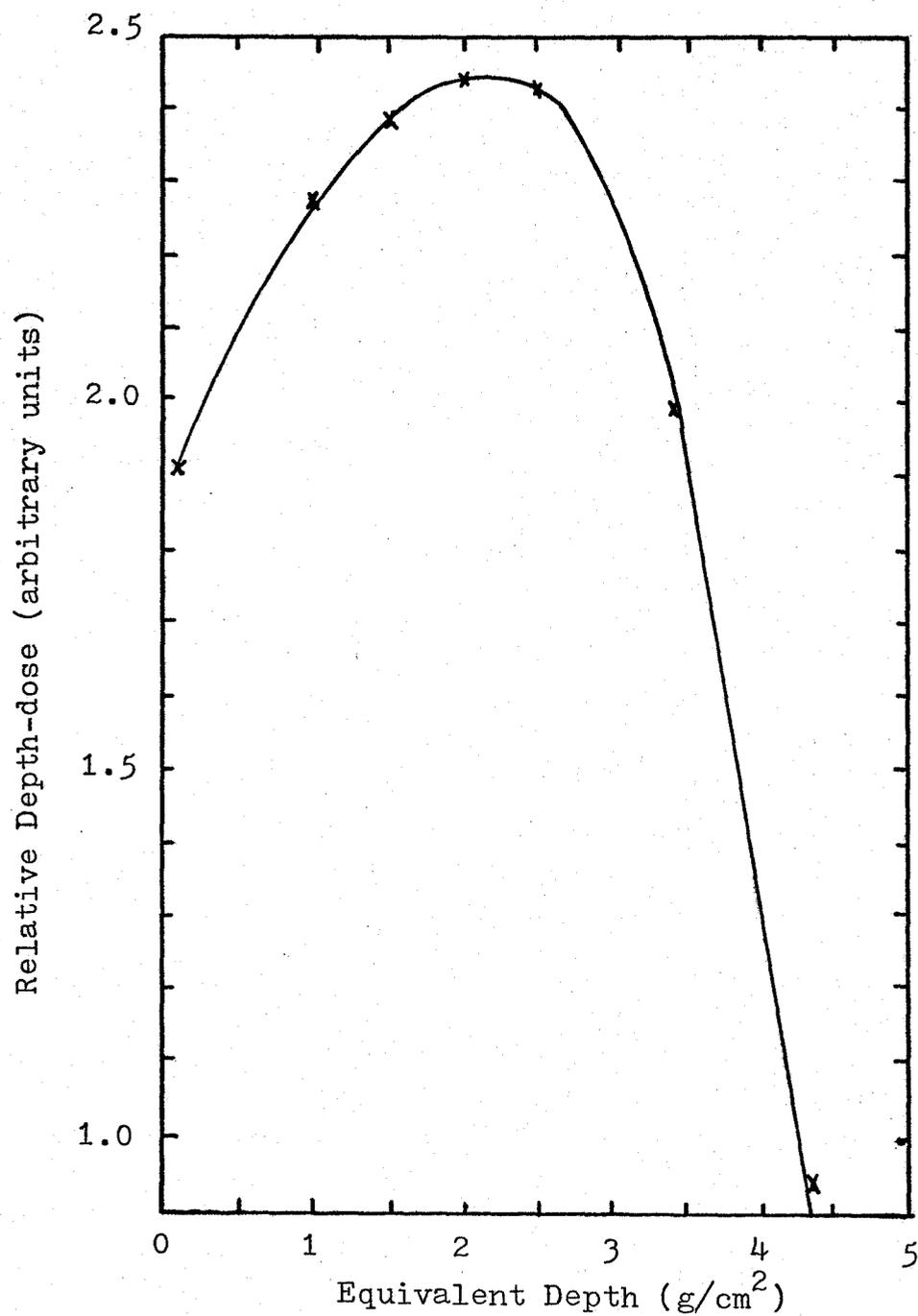


Figure 2. Depth-dose curves for 10 MeV electrons as measured using TLD's in a plastic phantom (Boese 1978).

13, 19, 25, and 32 MeV electrons. For the 10 MeV electrons with a depth-dose curve showing a rapidly changing slope over the diameter of the tube, however, it was found that the weighted mean was lower than the value at the center in all cases. The calculation predicted that the average absorbed dose in the dosimeter tube would be lower than the absorbed dose in the center by the following:

$(0.4 \pm 0.4) \% @ 2.0 \text{ cm depth}$
 $(0.8 \pm 0.4) \% @ 2.5 \text{ cm depth}$
 $(1.3 \pm 0.4) \% @ 3.0 \text{ cm depth.}$

Therefore it was necessary to correct the absorbed dose measurements at 10 MeV by these amounts.

3.3 Measurement of ΔOD

The value of ΔOD , the difference in the optical densities of the irradiated and control Fricke dosimeters required for the calculation of the absorbed dose according to Eqns. 13 or 14, was determined using a Baush & Lomb Model "Spectronic 710" Spectrophotometer (Baush & Lomb 1975). The spectrometer was set to measure absorption of 304 nm radiation in the dosimeter solution. Cuvettes made of U.V. silica quartz were used for holding the solution during the measurements. The optical pathlength of the cuvettes was 1.0 cm.

The determination of ΔOD proceeds as follows: The tubes containing the irradiated and control solutions were first placed in a thermostatically controlled water bath to maintain their temperature at 25°C (Fricke and Hart 1966). The cuvettes were thoroughly cleaned both inside and out using doubly distilled water followed by wiping the outside dry using soft, lint-free paper wipers. This completed, the spectrometer was zeroed using the control solution. First the cuvette is rinsed out using a portion of the solution; then it is filled at least one third full with the remainder. The cuvette containing the sample is then placed in a holder in the spectrometer capable of holding up to three cuvettes at a time. The temperature of the holder is maintained at 25°C by circulating water at this temperature through its core.

A second cuvette is then filled in the same manner with the control solution and placed in the holder. The spectrometer is zeroed on one of the cuvettes while the reading for the other is noted. This second cuvette containing control solution will remain in the holder throughout the remaining measurements to check for a drift in the zero point of the spectrometer.

The first cuvette is then removed from the holder and its contents discarded and replaced with irradiated solution. The cuvette is refilled using the same procedure of first rinsing with a portion of the solution to be

measured. The irradiated sample is then placed in the holder and the difference in the optical density between it and the control, ΔOD , is read directly off the three digit LED display of the spectrometer.

The procedure is then repeated for the other irradiated samples. If a large number of samples are to be read it is advisable to re-check the zero point after approximately every tenth sample using a fresh control sample and to periodically check the second cuvette for the formation of bubbles in the solution.

There are a number of routine precautions which must be taken throughout the measurements. One of the most important is to ensure that one does not at any time touch the faces of the cuvette through which the absorption is measured. The slightest amount of grease from one's fingers may drastically change the measured ΔOD . A good routine is to wipe off the faces each time before placing the cuvette in the holder. Also one must make sure that the solution has reached 25°C before the reading is taken. Finally one must make sure that the cuvette is placed in the holder using the same orientation for each reading. A rotation of 180 degrees might affect the reading with respect to a zero point shift.

3.4 System Calibration and Stability

The Fricke dosimeter system employed for the measurement of absorbed dose in these experiments was calibrated for absolute dose determination through comparison with the absorbed dose measured by calorimetry on the National Research Council ^{60}Co gamma radiation standard (Henry 1976,1978).

Two of the ionization chambers, the Capintec 1098 and the PTW 161244 (See Section 4.2), along with their associated electronics were calibrated on the NRC ^{60}Co source prior to their use in these experiments. For each chamber, the calibration provided a calibration factor for the exposure in air and the absorbed dose in water at a depth of 5 cm.

Using these, the calibration of the Fricke dosimeter system proceeded as follows: using the Theratron F ^{60}Co source at this facility, the exposure calibrations of the chambers were checked for reproducibility of the NRC results. Four series of measurements showed the reproducibility to be better than 1%. Now the absorbed dose as measured by the ionization chamber will be given by:

$$D_{\text{chamber}} = M N_c (C_{\lambda})_{\text{NRC}} \quad \text{Eqn. 15.})$$

where $(C_{\lambda})_{\text{NRC}}$ is the absorbed dose conversion factor for ^{60}Co determined from the NRC calibration measurements.

The absorbed dose in water measured simultaneously

using the calibrated ionization chambers and Fricke dosimetry on the ^{60}Co source. The calibration factor for normalizing the Fricke system to the NRC standard is then given by

$$\text{C.F. Fricke} = D_{\text{Fricke}} / D_{\text{chamber}} \quad \text{Eqn. 16.)}$$

where D_{Fricke} is given by Eqn. 14.

On the basis of four measurements, each involving eight Fricke dosimeters, the calibration factor was determined to be:

$$0.980 \pm 0.005$$

ie. the Fricke system was found to be reading 2% low.

Therefore all absorbed doses measured using this system were corrected by 2%.

The long term stability of the Fricke dosimetry system was also checked using the Theratron F ^{60}Co source. Three checks were made, each one consisting of three sets of eight dosimeters. The last check was made 34 days after the first. The results were corrected for the decay of the ^{60}Co source during this time.

The results are presented in Table II. As can be seen, the stability of the system is good to $\pm 1.2\%$ over this time. As added factor to be taken into account is that the three checks were each conducted using a different batch of dosimeter solution, indicating that there is no appreciable error introduced in the preparation of the dosimeter.

Checks on the short term stability of the Fricke

Table II
Long Term Stability of Fricke Dosimeter System

| Date | OD/min* | (OD/min)/(mean value) |
|---------|---------|------------------------|
| 15/6/78 | 5.300 | 0.989 |
| 15/6/78 | 5.417 | 1.011 |
| 15/6/78 | 5.375 | 1.003 |
| 25/6/78 | 5.352 | 0.999 |
| 25/6/78 | 5.352 | 0.999 |
| 25/6/78 | 5.352 | 0.999 |
| 18/7/78 | 5.356 | 1.000 |
| 18/7/78 | 5.356 | 1.000 |
| 18/7/78 | 5.356 | 1.000 |

Mean Value of (OD/min)/(mean value) = 1.000 ± 0.012
@ 95% confidence level.

* Corrected to 15/6/78 for decay of ^{60}Co .

dosimeter showed no observable variation for any of the measurements throughout the study.

4. IONIZATION CHAMBER DOSIMETRY

As was indicated in Eqn. 12, the experimental measurement of absorbed dose conversion factors requires the simultaneous measurement of the absorbed dose and of the apparent exposure at a point in water. The measurement of the absorbed dose in water using Fricke dosimetry has been discussed in detail in the previous chapter. In this chapter the measurement of the apparent exposure at a point in water using ionization chambers will be discussed.

4.1 Exposure Meters

Exposure measurements required for Eqn. 12 were made using three different ionization chambers, along with their associated electronics, which were calibrated in terms of ^{60}Co radiation as exposure meters.

The first of the chambers was a Capintec Model PR-06C air equivalent plastic Farmer replacement ionization chamber (Capintec 1976). The chamber used had the serial number 1098. It was constructed of air equivalent plastic with a sensitive volume of 0.65 ml, outer diameter of 7.0 mm, length of 22 mm, and a wall thickness of 0.28 mm or 50 mg/cm^2 . It was calibrated using the NRC ^{60}Co standard in June 1978.

The second chamber was a PTW* Model 30-332 Micro Chamber (Nuclear Associates 1973). The chamber used had the serial number 161244. It had a 0.10 ml nominal measuring volume with a 3 mm diameter and it was located at the end of a 100 cm long by 7 mm outer diameter water-tight rubber tube. No information was available with regard to its wall material or thickness. This chamber was also calibrated by the National Research Council in June 1978.

The third chamber used was a BaldwinFarmer[#] thimble chamber (Farmer 1954). The chamber used had a serial number 533702. It was constructed with a TUFNOL wall and nominal dimensions were as the case for the Capintec chamber. This chamber had not been calibrated at a standards laboratory for many years so was therefore calibrated in terms of the Capintec 1098 and PTW 161244 chambers using the Theratron F ⁶⁰Co source.

For all exposure measurements used in these studies, the chambers were used with an Electronics Instruments Ltd. (EIL) model 37C electrometer⁺. The particular unit used was the "EIL #2" of the Radiation Protection Branch of The Manitoba Cancer Treatment and Research Foundation. The unit was used in the integrated dose mode rather than the dose rate mode. For use with the Capintec 1098 and

* Physikalisches-Technische Werkstätten

Baldwin Instruments Co., Dartford, Kent, England.

+ Pitman Industries, Weybridge, Surrey, England.

BF533702 chambers the electrometer was set on the $10^5 \times 3$ range setting. For the PTW 161244 with its smaller sensitive volume, the $10^4 \times 3$ range was used. The voltage on the integrating capacitor of the electrometer was read using a Weston Schlumberger Model 6000 Autoranging digital multimeter*. The voltage in millivolts was read across a 330 ohm resistor.

The exposure meters were calibrated as described in the next section.

4.2 Exposure Calibrations

As can be seen from Eqn. 12, the apparent exposure measurement required for the determination of C or C_E consists of two parts: the corrected meter reading, M , which will be discussed in the next section, and the exposure calibration, N_c , for a calibration quality such as ^{60}Co which is provided by a national standards lab.

As stated the Capintec 1098 and PTW 161244 chambers were calibrated before the studies on the National Research Council ^{60}Co gamma standard (Henry 1978). The chambers were calibrated for use with a Townsend balance system constructed at the Manitoba Cancer Treatment and Research

* Weston Industries, Division of Schlumberger Canada Ltd., Mississauga, Ontario.

Foundation after a design by Farmer (1954). Unfortunately this transfer instrument was not suitable for measuring the high exposures required when measuring simultaneously with a Fricke dosimeter. It was therefore necessary to calibrate the EIL electrometer in terms of the transfer instrument before the chambers could be used in the studies.

The calibration of the exposure meters using the electrometer was carried out using the Theratron F ^{60}Co source. The calibration proceeds as follows: the chamber was set up in air with a 4 mm thick lucite buildup cap. The field size was set at 10 x 10 cm and the SSD to the cap at 75.0 cm. The chamber was connected to the transfer instrument and a series of exposures carried out. To eliminate any error associated with the opening and closing of the shutter on the source, exposures of various time durations were made and their difference used to determine the relation between the exposure per unit time and the reading of the transfer instrument.

This completed, without disturbing the SSD or chamber positioning the chamber was disconnected from the transfer instrument and connected to the EIL electrometer. The process of exposing the chamber was repeated and the relation between the exposure per unit time and electrometer reading determined.

Using these two figures it was possible to determine the relative sensitivity of the two systems and thus the

exposure calibration factor in Roentgens per millivolt for the exposure meter employing the EIL electrometer. This process was carried out for the Capentec 1098 and PTW 161244 ionization chambers. The BF 533702, for which there was no direct NRC calibration on the transfer instrument, was calibrated in terms of the Capentec 1098 chamber which operated using the same range setting on the EIL.

Periodic checks of the calibration were carried out on the Theratron F with a fixed geometry for the duration of the studies. For these checks, the transfer instrument was not normally employed but rather the calibration factor for the EIL system was checked for stability after the necessary corrections were made for temperature and pressure (See Section 4.3), and decay of the ^{60}Co source. These checks showed the calibration factor to be stable to within $\pm 0.4\%$.

The exposure calibration factors for the three chambers used are given in Table III. The error quoted is twice the standard deviation of the individual measurements making up the mean. The number of readings from which the mean was calculated is also given.

Table III
 ^{60}Co Exposure Calibration Factors

| Chamber | EIL Range | # of Readings | Calibration Factor |
|--------------------------|-----------------|---------------|----------------------|
| Capintec 1098 | $10^5 \times 3$ | 6 | 5.54 ± 0.01 R/mV |
| PTW 161244 | $10^4 \times 3$ | 6 | 3.70 ± 0.03 R/mV |
| Baldwin-Farmer 533702 | $10^5 \times 3$ | 10 | 6.48 ± 0.02 R/mV |

4.3 Meter Reading Corrections

The second term in the expression for apparent exposure in Eqn. 12 is M, the meter reading of the exposure meter proportioned to the charge collected. As stated, it is necessary to correct this reading for temperature, pressure, and lack of saturation.

The majority of standard ionization chambers are made with their sensitive volume vented to the environment via a small canal. The reason for doing this is that in a sealed ionization chamber, the chamber gas may have its composition altered due to such factors as absorption or oxidation by the chamber walls or electrodes, outgassing, etc. This in turn will affect the long term stability of the device. Having the chamber vented eliminates these problems.

The use of a vented chamber, however, requires that compensations be made for variations in chamber air density as a result of variations in probe temperature and atmospheric pressure. The correction factor introduced to account for these variations is:

$$CF_{(T+P)} = (760/P) \times (T/295) \quad \text{Eqn. 17.})$$

where P is the atmospheric pressure in mm Hg at the time of measurement and T is the temperature of the ion chamber (not the room temperature) in degrees Kelvin. The values of 760 mm Hg and 295 K are the conditions for the NRC calibration.

This correction factor was applied to all exposure readings taken during this study.

The second correction to the meter reading which must be made in determining the apparent exposure is that for lack of saturation (Boag 1966). This refers to the inability of the chamber electrodes to collect all the charge created in the sensitive volume. Factors affecting how efficient a particular chamber will be at collecting the charge produced within its volume include: the volume rate of charge formation which in turn depends on the nature of the radiation source; the electron and ion mobilities; the recombination rates; and the electric field strength (Holt et al. 1978).

The efficiency of an ionization chamber is defined as the rate of the rate of charge collection within the chamber to the rate of charge production. As the voltage difference between the electrodes is increased from zero to a high value, the efficiency, or more specifically the current representing the charge collected increases until it approaches asymptotically the saturation current for the given radiation quality and intensity. This saturation current represents that which would be measured if all ions and electrons formed in the chamber by radiation were to reach the electrodes. Typical saturation curves for chambers used in pulsed electron beams are shown in Figure 3.

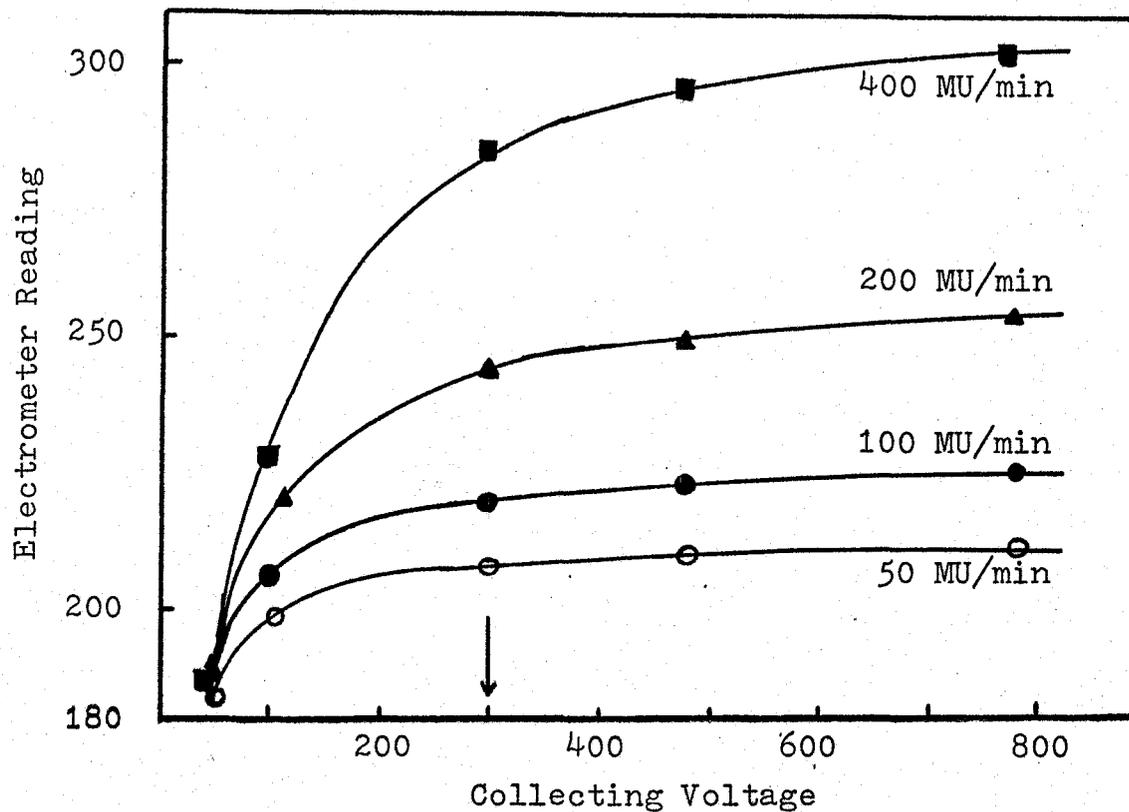


Figure 3a. Saturation curves for BF 533702 chamber used in 32 MeV electron beam. Arrow indicates the 300 V operating level of the chamber. (from Cormack 1978).

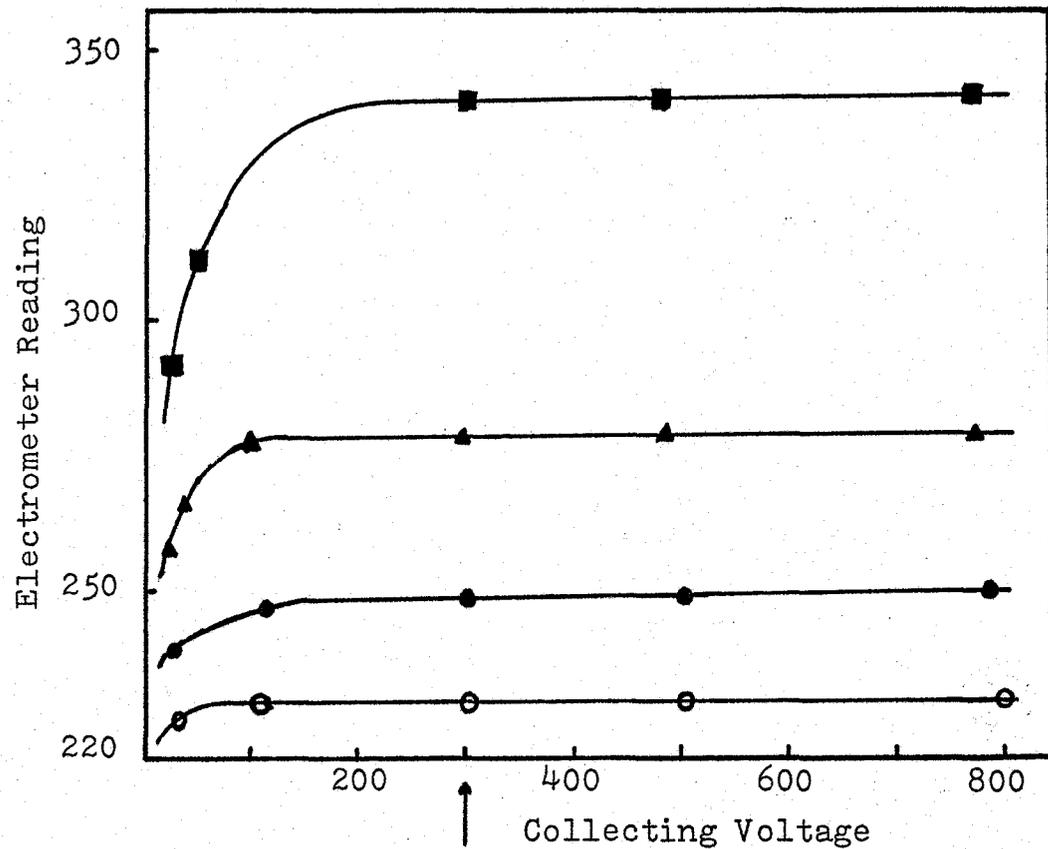


Figure 3b. Saturation curves for PTW 54644 chamber used in 32 MeV electron beam. Arrow indicates the normal 300 V operating level of the chamber. Note that this is not the PTW chamber used in the present study but another PTW chamber of the same design. (From Cormack 1978).

Boag (1966) has derived an efficiency formula for ionization chambers used with pulsed radiation:

$$\begin{aligned} f &= \text{charge collected/charge produced} \\ &= u^{-1} \ln(1+u) \end{aligned} \quad \text{Eqn. 18.)}$$

where $u = tr/V$. t is a parameter characteristic of the chamber and the gas it contains, r is the charge liberated per unit volume per pulse in the gas, and V is the collecting voltage on the electrodes.

In order to be able to use Eqn. 18 for determining the chamber efficiency at a given collecting voltage, V , it is necessary to determine the values of t and v for the radiation qualities and intensities of interest. Since t is a characteristic of the chamber and r is a characteristic of the beam quality and intensity, however, it is possible to do so by measuring the collection current as a function of collection voltage in each case as was done for the curves in Figure 3. It is then possible to solve for tr by fitting the experimentally determined points to Eqn. 18. It was found that this is best done using an iterative fitting technique.

The points required for the fit were obtained by setting the collection voltage on the electrodes of the ionization chamber and then measuring the reading on the EIL electrometer for a given amount of radiation. Since all C_E and C_λ measurements were made using the 200 MU/min

setting on the Sagittaire accelerator, efficiency measurements were only made for this dose rate. The collection voltage was then varied and the procedure repeated. This was done for each of the radiation qualities of interest in the present studies. The data obtained in this way was then fitted as described and the values of τ obtained used to determine the collection efficiency for a collecting voltage of 300 V, ie. that used in normal operation of the exposure meters. A correction factor for the lack of saturation in the chamber is then given by the reciprocal of f .

The correction factors for three chambers used in these studies determined by the method described above are given in Table IV. These correction factors were applied to all exposure readings taken during these studies.

4.4 Point of Measurement

Experimental comparisons of thimble and parallel plate ionization chambers have shown that the point of measurement in a thimble chamber is displaced from the centre of the chamber towards the source of the electron beam (Hettinger et al. 1967). On the basis of a number of experimental and theoretical calculations, ICRU 21 (1972) recommends the point of measurement being taken as $3r/4$ in front of the centre of the chamber where r is the radius of

Table IV
Correction Factors for Lack of Charge Saturation

| Radiation Quality | Capintec 1098 | PTW 161244 | B.F. 533702 |
|----------------------|------------------|---------------|----------------|
| 32 MeV | 1.051 | 1.018 | 1.07 |
| 25 | 1.035 | 1.011 | 1.045 |
| 19 | 1.024 | 1.006 | 1.035 |
| 13 | 1.018 | 1.007 | 1.025 |
| 10 | 1.020 | 1.006 | 1.03 |
| 25 MV x-rays | 1.008 | 1.003 | 1.013 |
| ^{60}Co | 1.000 | 1.000 | 1.000 |

All values are for -300V collecting voltage on the chamber and a 200 MU/min dose rate setting on the Sagittaire.

the active gas volume.

Because of constraints introduced by the apparatus used in the absorbed dose conversion factor measurements, it was not possible to move the chamber back to a depth where its point of measurement would be the same as the centre point of the Fricke dosimeter tubes (See Section 5.2). It was, therefore, necessary to correct the apparent exposure reading back to the point at the centre of the tubes. This was done by once again employing the depth dose data given in Figures 1 and 2. The correction factor was determined as the ratio of the dose at the depth corresponding to the centre of the chamber to the dose at the depth corresponding to the point of measurement. For determining the point of measurement, the radii of the chamber active volumes were taken as 3.2 mm for the Capentec 1098 and Baldwin-Farmer 533702 and as 1.5 mm for the PTW 161244. These figures were taken from the manufactures specifications and can be assumed to be correct to ± 0.1 mm.

The correction factors determined for each of the electron beams employed are given in Table V. These were multiplied by all exposure measurements made in determining the absorbed dose conversion factors.

Table V
Displacement Correction Factors

| Electron Energy (MeV) | Depth at Chamber Center (cm) | Capintec 1098 & BF 533702 | PTW 161244 |
|-----------------------|------------------------------|---------------------------|------------|
| 32 | 3.0 | 1.00 | 1.00 |
| 25 | 3.0 | 1.00 | 1.00 |
| 19 | 3.0 | 1.01 | 1.00 |
| 13 | 3.0 | 1.01 | 1.00 |
| 10 | 3.0 | 0.96 | 0.99 |
| 10 | 2.5 | 1.00 | 1.00 |

5. EXPERIMENTAL DETERMINATION OF C_E AND C_λ

5.1 Experimental Objectives

As stated at the end of Chapter 2, a great deal of confusion presently exists concerning the absorbed dose conversion factors C_E and C_λ . Therefore the main objective of the present study was to obtain reliable experimental results which might lead to a better understanding of the situation.

The experimental determination of all values of C_E and C_λ used for dosimetry in standard radiotherapy conditions, however would require a study of enormous magnitude requiring the collection of data over a period of several years. Because of constraints placed by the time available in which it might be completed, it was necessary to limit the present study to a number of well-defined objectives.

The first of these was to determine C_E as a function of electron energy at a depth of 3.0 cm in a water phantom. This was to be done for each of the chambers and their results compared. The depth of 3.0 cm was chosen as a convenient point for comparison with other works, the ICRU recommendations, and theories. Along with the C_E values, values of C for ^{60}Co and 25 MV x-rays were to be

determined for all chambers. The above radiation qualities were chosen on the basis of availability for use in these experiments.

Recent work by Almond and Svenson (1977) and other groups has indicated that the material surrounding the chamber during the irradiation in a water phantom, ie. the sleeve and/or ^{60}Co buildup cap, may influence the exposure meter readings in some cases. Kutcher et al. (1977) have also noted that some confusion exist as to whether or not the ^{60}Co buildup cap used during calibration should remain on the chamber when it is used with higher energy radiations. Therefore one of the objectives of this study was to compare the effects of various sleeves on the values of C_E and C_λ measured.

Finally, it was decided to investigate the effect of phantom material on the measurement of absorbed dose conversion factors. Although it is generally recommended that all measurements be carried out in a water phantom (ICRU 1969, 1972), some authors (See for example Kartha and MacDonald 1970) have published results for measurements of C_E or C_λ which were conducted using a phantom of a plastic such as polystyrene. The use of a plastic phantom enjoys the advantages of simpler measurement procedures and more accurate positioning of dosimeters and ionization chambers. Therefore a study was made of the effect of phantom material on absorbed dose and exposure measurements

going into the determination of the conversion factors.

5.2 Apparatus and Procedure

All measurements of the absorbed dose conversion factors made during this study were made using the AECL-CGR Therac 40/Sagittaire (AECL 1974) linear accelerator and the Theratron F ^{60}Co * source at the Manitoba Cancer Treatment and Research Foundation.

The Sagittaire accelerator is an electron accelerator which produces electron beams of 7, 10, 13, 16, 19, 22, 25, 28, and 32 MeV energies. In addition it may be used to produce a beam of x-rays with a maximum energy of 25 MV. The output of the Sagittaire is a pulsed beam which is scanned across the field in a sawtoothed pattern. The beam is scanned horizontally at 0.615 Hz and vertically at a frequency of 4 Hz. The dose rate may be set at 50, 100, 200 or 400 monitor units (MU) per minute. All studies were carried out at 200 MU/min. for all qualities.

The radiation qualities chosen for the studies were 10, 13, 19, 25, and 32 MeV electrons, 25 MeV x-rays, and ^{60}Co gamma rays. The particular electron energies chosen were selected in order to provide a reasonable

* Atomic Energy Canada Ltd., Ottawa

coverage of the available range in an energy related study*.

The 25 MV x-ray beam used had a broad energy spectrum with a maximum photon energy of 25 MeV. It was produced using a stopping production target. Since it was the only high energy x-ray beam available on the Sagittaire accelerator, it was not possible to investigate C_2 for any other high energy photons.

For the measurements made using 10, 13, or 19 MeV electrons, extra collimation was used to provide a flatter beam profile.

All studies conducted on the Sagittaire were made using a $20 \times 20 \text{ cm}^2$ field size, a 100 cm SSD and a dose rate of 200 MU/min. The Theratron F ^{60}Co unit was employed with a $20 \times 20 \text{ cm}^2$ field and a 75 cm SSD. The smaller SSD was used to provide a higher dose rate. The dose rate under these conditions was of the order of 165 rads/min. at a depth of 3.0 cm in a phantom. With the exception of a few measurements with 10 MeV electrons carried out at a depth of 2.5 cm, all studies were made at a depth of 3.0 cm (or 3.0 g/cm^2) in a water or lucite phantom. All dosimeters and exposure meters were positioned with their axis perpendicular to the axis of the beam.

* Although a 7 MeV electron beam was available on the Sagittaire, it proved unsuitable for use in the present study because of its very shallow depth-dose curve.

For measurements in water, a 40 x 40 x 60 cm tank was used. It was constructed from 6.25 mm lucite sheets. The edges of the tank were reinforced with lucite strips to prevent bowing of the sides when it was filled with water. The ends perpendicular to the beam were marked with horizontal and vertical lines to facilitate alignment of the tank and positioning of the dosimeters. The temperature of the water in the tank was $(25 \pm 0.5)^{\circ}\text{C}$ for all measurements.

The Fricke dosimeter tubes were held in a rack specifically designed for this purpose. When in place in the tank, the rack suspended the tubes so that they were centered in the vertical plane. It could also be moved in the horizontal plane to allow for easy positioning. Although the rack could hold up to 24 dosimeter tubes, normally only eight were used in each measurement. A top view of the rack, showing the normal positioning of the tubes is shown in Figure 4. The depths indicated are the depth in the phantom at the center point of the tube when it is in place in the phantom. This includes the equivalent depth added by the thickness of the 6.25 mm lucite entrance window. The number beside the position of each tube indicates typical ΔOD readings for that tube after irradiation with 3996 monitor units of 25 MeV electrons.

Also shown in Figure 4 is the position of the ionization chamber for measurement of the apparent exposure. The chambers were placed in specially designed holders and

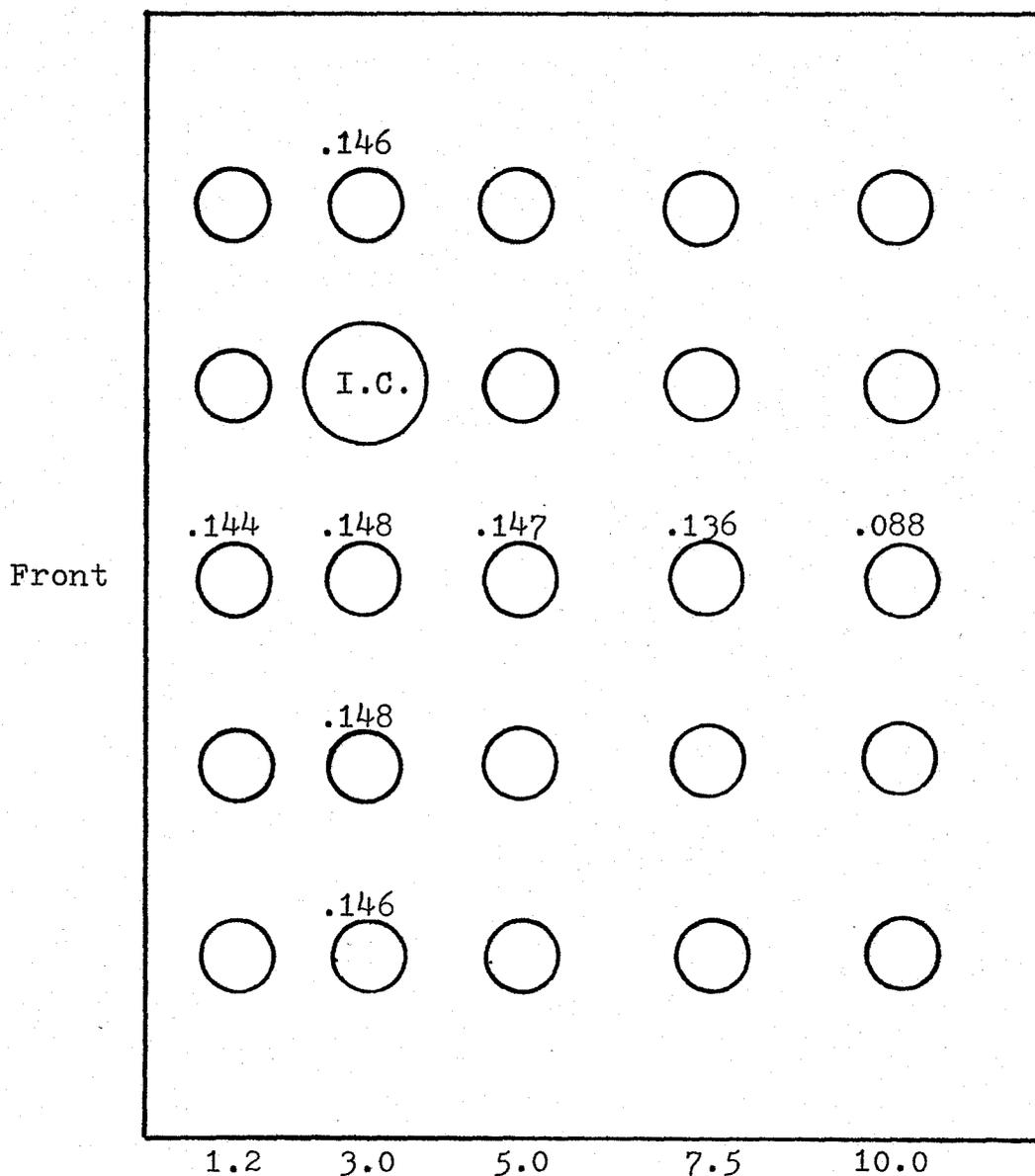


Figure 4. Rack for holding FeSO_4 dosimeters.

Top view is shown. Dosimeters were normally placed in the positions indicated by the numbers. The numbers are the OD readings for the dosimeters after an irradiation with 25 MeV electrons. The numbers along the lower edge of the figure indicate the depth in the phantom at the center point of the tubes in that row. I.C. refers to the position of the ionization chamber in the phantom.

were suspended vertically into the tank so that the center point of their active volumes corresponded with the center of the horizontal field. The holders were held secure in an adjustable frame which fit over the tank. Holders were available for all chambers used with various sleeves or buildup caps.

The sleeves available for the various chambers were: 2.0 and 4.5 mm thick lucite for use with the Capintec 1098; 4.5 mm thick lucite for use with the PTW 161244 which could be used in water without a protective sleeve; 4.5 mm thick lucite and approximately 0.5 mm rubber for use with the BF 533702. Each of the chamber-sleeve combinations was investigated at each of the radiation qualities used for the possible influence of the sleeve on the conversion factor.

For the phantom material comparison, a phantom constructed of lucite was used along with the water phantom. This phantom consisted of two pieces of lucite, 15 cm L x 20 cm W x 2.5 cm D and 10 cm L x 20 cm W x 2.5 cm D. Along one 20 cm edge of the large piece were drilled 5 holes on 15 mm centers which were centered with respect to the width and depth of the slab. Four of the holes were 12 mm diameter by 63 mm deep to accommodate the Fricke dosimeter tubes. The fifth hole, immediately to one side of the center, was made to accommodate a Farmer type chamber with a 7 mm outer diameter at its sensitive volume.

The second lucite slab had similarly spaced holes drilled to accommodate the caps of the dosimeter tubes and the cable of the ionization chamber. The two slabs fit snugly together to form an enclosure for the dosimeters and ionization chamber. The depth of the point at the center of a tube in the phantom was 1.5 g/cm^2 *. To achieve a depth equivalent to 3.0 cm of water, sheets of lucite were placed on top of the phantom during irradiation. Conditions under which the measurements were made in the lucite phantom were identical to those for the water phantom with the exception of the gantry angle. For the lucite the gantry was set at 0° while an angle of 90° was used with the water phantom. Also the dosimeters and ion chambers were at room temperature for use with the lucite rather than 25 C.

The dose required for approximately 1% accuracy with Fricke dosimetry is of the order of 4 kilorads (Fricke and Hart 1966). Therefore this absorbed dose value determined the exposure time for all measurements. On the Sagittaire this corresponded to approximately 3996 monitor units. Therefore each irradiation consisted of four sets of 999 MU. The equivalent exposure level on the ^{60}Co unit corresponded to about 25 minutes of irradiation.

For all measurements the ionization chamber and the Fricke dosimeters were irradiated simultaneously. This was done to eliminate any error which might come about as

* Assuming 1.18 g/cm^3 as the density of lucite.

a result of any fluctuations in the output of the linear accelerator from one irradiation to the next. Since all measurements were ultimately concerned with the ratio of the two measured quantities, any problems which might arise as a result of a fluctuation in output would thus be eliminated.

5.3 Data Analysis

The starting point for the analysis of the data obtained in these experiments was the determination of ΔOD , the change in optical density of the irradiated Fricke dosimeter. The ΔOD for each of the Fricke dosimeters in the irradiated set is determined as was described in Section 3.3. The value of ΔOD that would be expected for a dosimeter in the place of the ionization chamber is then determined from the values measured for the four tubes centered at the same depth as the chamber. This number was then used to determine $\Delta OD/MU$, ie. a number proportional to the absorbed dose in the dosimeter per unit of radiation as measured by the control systems of therapy units.

Similarly, the reading of the exposure meter, first corrected for temperature and pressure, was used to determine mV/MU , ie. the meter reading in millivolts per unit of radiation, a number proportional to the apparent exposure

per unit of radiation. These two numbers were then used to determine $\Delta OD/mV$, a number which is directly proportional to the absorbed dose conversion factors for the radiation quality in question.

At this point the analysis proceeded in one of two directions. If the data was to be used for the determination of absorbed dose conversion factors, the necessary proportionality constants and correction factors were introduced. If it was to be used for either the sleeve or phantom comparisons, however, these factors were not introduced.

The reason for this is that all the comparisons were conducted with each measurement employing the same chamber under the same conditions. The only changes made were those necessary for the comparison. The only correction necessary was that for temperature and pressure which had been introduced by that point. Simply comparing the OD/mV for each of the two cases made the calculations simpler and less prone to error.

The analysis of the sleeve comparison data simply involved determining, for each chamber at each quality, the ratio of the OD/mV recorded with one type of sleeve to the OD/mV recorded for the other. This was done for each energy of each sleeve-chamber combination investigated. The results are presented in Section 6.2.

The same procedure was also used for the analysis of the phantom comparison data with these results presented in Section 6.1.

Analysis of the data for absorbed dose conversion factors, however, was more complex. Dividing Eqn. 14 (with the G value appropriate to the radiation quality in question) by the exposure calibration factor for the chamber in question resulted in the proportionality factor linking the OD/mV to the absorbed dose conversion factor, ie.:

$$\text{P.F.} = \frac{2.723 \times 10^4}{\text{exposure calibration}} \quad \text{Eqn. 19a.)}$$

for electrons and 25 MV x-rays, or

$$\text{P.F.} = \frac{2.758 \times 10^4}{\text{exposure calibration}} \quad \text{Eqn. 19b.)}$$

for ^{60}Co .

It was also necessary to apply the various correction factors discussed in previous sections. These include: 1) the normalization factor for the absolute calibration of the Fricke dosimeter system (Section 3.4); 2) a factor to account for the finite width of the dosimeter tubes (Section 3.2); 3) a factor to account for the lack of saturation in the ionization chamber (Section 4.3); and a factor accounting for differences in the depth dose curve between the point of measurement and the centre of the chamber (Section 4.4). Combining these we may achieve a single correction

factor for use in the determination of the absorbed dose conversion factors:

$$C.F. = \frac{\text{Normalization factor} \times \text{Width factor}}{\text{Saturation factor} \times \text{Displacement factor}} \quad \text{Eqn. 20.)}$$

Using the data given in the sections listed above, this correction factor was determined for each case of interest in the present study. The results of the calculations are given in Table VI.

The absorbed dose conversion factor for the radiation quality in question is now given by:

$$C = D/MN_c \\ = (\Delta OD/mV) \times P.F. \times C.F. \quad \text{Eqn. 21.)}$$

where $\Delta OD/mV$ is corrected for temperature and pressure and P.F. and C.F. are given by Eqns. 19 and 20 respectively. All conversion factors were determined in this way and the results of the calculations are given in Sections 6.3 and 6.4.

Uncertainties were estimated for each quantity by combining the systematic and statistical errors involved in the determination of that quantity. The errors were combined by taking the square root of the sum of the squares of each of the errors (ICRU 1969, 1972). All uncertainties are expressed at 95% confidence levels.

Table VII gives the total uncertainty in the

Table VI
Overall Correction Factors*

| Radiation Quality | Depth at Chamber Center (cm) | Capintec 1098 | BF 533702 | PTW 161244 |
|-------------------|------------------------------|---------------|-----------|------------|
| 32 MeV | 3.0 | 0.971 | 0.953 | 1.002 |
| 25 | 3.0 | 0.986 | 0.976 | 1.009 |
| 19 | 3.0 | 0.986 | 0.976 | 1.014 |
| 13 | 3.0 | 0.992 | 0.985 | 1.013 |
| 10 | 3.0 | 1.054 | 1.043 | 1.037 |
| 10 | 2.5 | 1.008 | 0.998 | 1.022 |
| 25 MV x-rays | 3.0 | 1.012 | 1.007 | 1.017 |
| ^{60}Co | 3.0 | 1.020 | 1.020 | 1.020 |

* For application after temperature and pressure corrections have been made.

Table VII
 Uncertainty (in %) in the Absorbed Dose Conversion Factors

| Source of Error | Radiation Quality | | | | | | |
|--------------------|-------------------|-----|-----|-----|-----|------|------------------|
| | 32 | 25 | 19 | 13 | 10 | 25MV | ⁶⁰ Co |
| ΔOD | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| mV | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Eqn. 19 (P.F.)* | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Correction Factors | 2.0 | 2.0 | 2.0 | 2.0 | 3.0 | 1.5 | 0.5 |
| G value | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 1.3 |
| Sum without G | 2.7 | 2.7 | 2.7 | 2.7 | 3.5 | 2.3 | 1.8 |
| Sum with G | 4.8 | 4.8 | 4.8 | 4.8 | 5.3 | 4.6 | 2.2 |

* not including error in G.

determination of the absorbed dose conversion factor for each of the radiation qualities discussed in this report. Each of the contributing error sources is listed for each case. For each quality, two values of the total error are given, one including the error in the Fricke dosimetry G value, the other not. In the context of the present report, the value not containing the G value error is likely the more relevant. Assuming the G value is a constant for all electron energies used, an error in this value would only shift all of the values for C_E determined but would not affect the energy dependence of C_E . Nor would it affect a comparison of chambers, phantoms, or sleeves. Thus the lower value given in Table VII, ie. that not including the error in G, is likely the more relevant of the two.

6. Results

6.1 Phantom Comparisons

The comparisons of the lucite and water phantoms was conducted using the Capentec 1098 and BF 533702 ionization chambers. All measurements were made at a depth of 3.0 g/cm^2 . For each measurement, the value of ΔOD at the point of the ion chamber was estimated using the values derived from four Fricke dosimeters located at the same depth.

For each radiation quality investigated, the value of $(\Delta\text{OD}/\text{mV})$ was determined for each of the phantom systems. The comparison of the phantoms was accomplished by taking the ratio of the (OD/mV) in lucite to the same quantity in water. The results are presented in Table VIII.

From the data presented in the table, it would appear that there is no observable difference between measurements made in water and those made at an equivalent depth in lucite. There would not appear to be any relation between the ratios presented and the radiation quality for which they were measured. Nor would there appear to be any difference between the results obtained using two different chambers.

Two notes of caution should be made concerning these results, however. The first is that the comparisons

Table VIII
Comparison of Lucite and Water Phantoms

| Chamber | Radiation Quality | $\frac{(\text{OD/mV})_{\text{luc}}}{(\text{OD/mV})_{\text{H}_2\text{O}}}$ |
|---------------|-------------------------|---|
| BF 533702 | ^{60}Co | 1.018 |
| | ^{60}Co | 0.990 |
| | 25MV | 1.004 |
| | 32 | 0.998 |
| | 19 | 0.998 |
| | 10 | 1.003 |
| | 10 | 0.999 |
| | $m^* = 1.001 \pm 0.018$ | |
| Capintec 1098 | ^{60}Co | 0.997 |
| | ^{60}Co | 0.990 |
| | 25MV | 1.034 |
| | 25MV | 1.014 |
| | 25MV | 0.994 |
| | 32 | 0.997 |
| | 19 | 1.006 |
| | $m = 1.005 \pm 0.030$ | |

Average for both chambers: $m = 1.003 \pm 0.024$

* mean value \pm two standard deviations. 95% confidence level.

were conducted using different gantry angles for the phantoms. Regular checks of the output beam of the Sagittaire accelerator have shown the output to vary with gantry angle in spite of the fact that the internal dosimetry system of the machine records the same output for all cases (Boese 1978). Although it has not been possible to establish a relationship between the gantry angle and the exposure per monitor unit, there remains the possibility that such a relationship may exist and has influenced the results presented in Table VIII.

Secondly, it must be remembered that it is the $\Delta OD/mV$ for each phantom that is being compared here. It was observed during the measurements that either the ΔOD or the meter reading ratios on their own could vary to a much larger degree than indicated by the data in the table. This would indicate the need for caution when using any one of the dosimetry systems independently.

6.2 Sleeve Comparisons

The study comparing the effect of the chamber sleeve on the measurements of the absorbed dose conversion factors in water were made using all three of the ionization chambers available. Comparisons were made of the various sleeve-chamber combinations given in Section 5.2. These

were made in the same fashion as was done in the phantom comparison described in the previous section. Since a 4.5 mm thick lucite sleeve was common to all comparisons, all data is given as the ratio of the OD/mV measured with a given chamber with a given sleeve to the same quantity for the same chamber with the 4.5 mm thick sleeve at the same radiation quality. The results of the comparison are given in Table IX.

As can be seen from the table, there does not appear to be any observable difference in the measurements due to the sleeve material or thickness. This would appear to be true for all chambers at all qualities studied.

These results would appear to disagree with the statement made by Kutcher et al. (1977) that there should be at least a one or two percent difference observed when a buildup cap is used for photon energies above 20 MeV. The results for the three chambers used with the 25 MV x-ray beam showed a mean ratio for four measurements of 1.006 ± 0.026 . While a result based upon only four measurements cannot be considered conclusive, it would appear to indicate that there is no serious problem associated with the use of a buildup cap on a chamber used with high energy photons.

Similarly, it would appear that a sleeve thickness up to 0.46 g/cm^2 would have no effect on measurements made with an ion chamber for high energy electron beams.

Table IX
Sleeve Comparison Results

| Radiation Quality | Capintec 1098 (2.0 mm lucite) | PTW 161244 (none) | BF 533702 (0.5 mm rubber) |
|---------------------------|-------------------------------------|-------------------------|---------------------------------|
| ^{60}Co | | 0.992* | |
| 25MV | 1.022 | 0.992 | 1.009 |
| 25MV | | 1.000 | |
| 32 | 1.000 | 1.000 | 0.984 |
| 32 | | 1.000 | |
| 25 | 0.994 | 1.000 | |
| 19 | 0.994 | 1.009 | |
| 13 | 1.000 | 1.000 | |
| 10 | 1.000 | 1.025 | 1.011 |
| 10 | 1.006 | 1.000 | |
| Mean \pm | 1.002 \pm | 1.002 \pm | 1.001 \pm |
| 2 x standard deviation | 0.020 | 0.018 | 0.030 |

Overall mean for all chambers: $m = 1.002 \pm 0.020 @ 95\% \text{ C.L.}$

* Numbers indicate $(\text{OD/mV})_A / (\text{OD/mV})_B$ where A refers to the sleeve listed below the chamber and B refers to a 4.5 mm thick lucite sleeve.

6.3 C_E Measurements

With the exception of three measurements at a depth of 2.5 g/cm^2 in lucite, all studies of the absorbed dose conversion factors for electrons, C_E , were carried out at a depth of 3.0 g/cm^2 in either water or lucite. The data obtained in these measurements were analysed as discussed in the previous chapter. The results of the study are presented in Table X and Figure 5.

Also shown in the table are the ICRU 21 (1969) values recommended for 6.0 mm and 3.0 mm diameter chambers for comparison with the Farmer type and PTW chambers respectively. It can be seen that the measured values all fall below the ICRU recommendations. Table XI gives the ratio of the recommended value to the measured value for each chamber. These are also shown graphically in Figure 6.

From these it can be seen that the measured values were of the order of 3% lower. The greatest discrepancies would appear to be for the highest and lowest qualities studied, with the 19 and 25 MeV beams showing the closest agreement with the recommended values. No chamber would appear to be in better agreement with the ICRU values than the other two. The only detectable difference in C_E values amongst the chambers used was that predicted on the basis of the difference in the sensitive volumes.

Figure 7 shows a comparison of the C_E values determined in this study to those determined experimentally

Table X
Measured C_E Values

| Radiation Quality | Depth | Capintec 1098 | BF 533702 | PTW 161244 | ICRU 21* | |
|----------------------|-------|------------------|--------------|---------------|----------|------|
| | | | | | 6mm | 3mm |
| 32 | 3.0 | 0.78(5)** | 0.77(5) | 0.79(4) | 0.81 | 0.81 |
| 25 | 3.0 | 0.82(3) | 0.81(1) | 0.81(2) | 0.83 | 0.83 |
| 19 | 3.0 | 0.82(3) | 0.81(2) | 0.84(2) | 0.84 | 0.85 |
| 13 | 3.0 | 0.84(2) | 0.84(1) | 0.87(2) | 0.88 | 0.89 |
| 10 | 3.0 | 0.87(5) | 0.86(7) | 0.87(4) | 0.90 | 0.91 |
| 10 | 2.5 | 0.85(1) | 0.86(2) | | 0.89 | |

* ICRU 21 values for 6.0 mm and 3.0 mm diameter chambers respectively.

** The number in brackets is the number of measurements upon which the average value presented was determined.

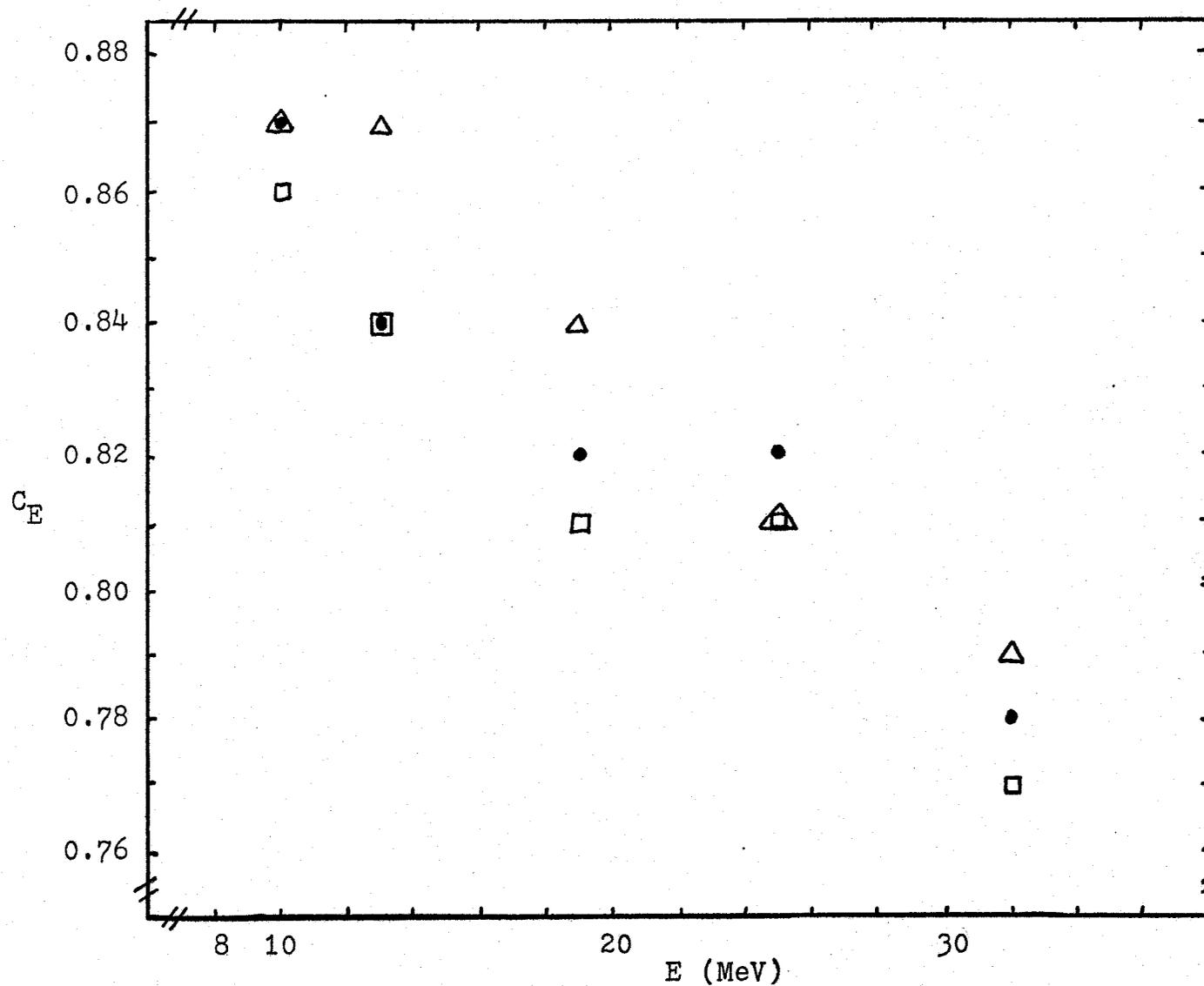


Figure 5. C_E vs Initial Electron Energy. All measurements made at a depth of 3.0 g/cm^2 . (●) Capintec 1098, (□) BF 533702, (△) PTW 161244.

Table XI

Ratio of Predicted to Measured Values of C_E

$$\frac{C_E(\text{ICRU})}{C_E(\text{measured})}$$

| Radiation Quality | Depth | Capintec 1098 | BF 533702 | PTW 161244 |
|---------------------------|-------|------------------|-----------------|-----------------|
| 32 | 3.0 | 1.04 | 1.05 | 1.03 |
| 25 | 3.0 | 1.01 | 1.02 | 1.02 |
| 19 | 3.0 | 1.02 | 1.04 | 1.01 |
| 13 | 3.0 | 1.05 | 1.05 | 1.02 |
| 10 | 3.0 | 1.03 | 1.05 | 1.05 |
| 10 | 2.5 | 1.05 | 1.03 | |
| Mean Ratio $\pm 2 \sigma$ | | 1.03 \pm 0.03 | 1.04 \pm 0.02 | 1.03 \pm 0.02 |

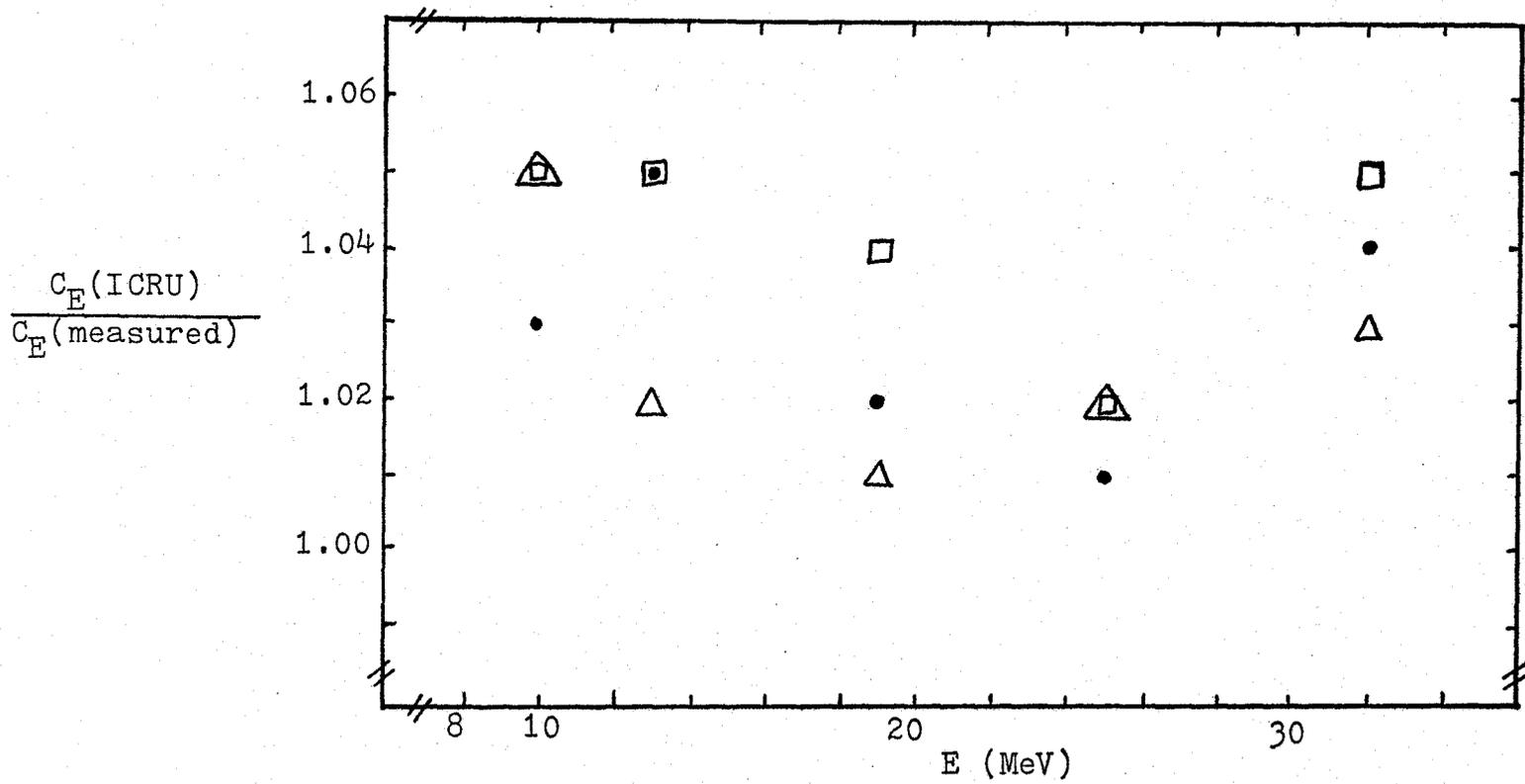


Figure 6. $C_E(\text{ICRU})/C_E(\text{measured})$ vs Initial Electron Energy.
 (●) Capintec 1098, (□) BF 533702, (△) PTW 161244.

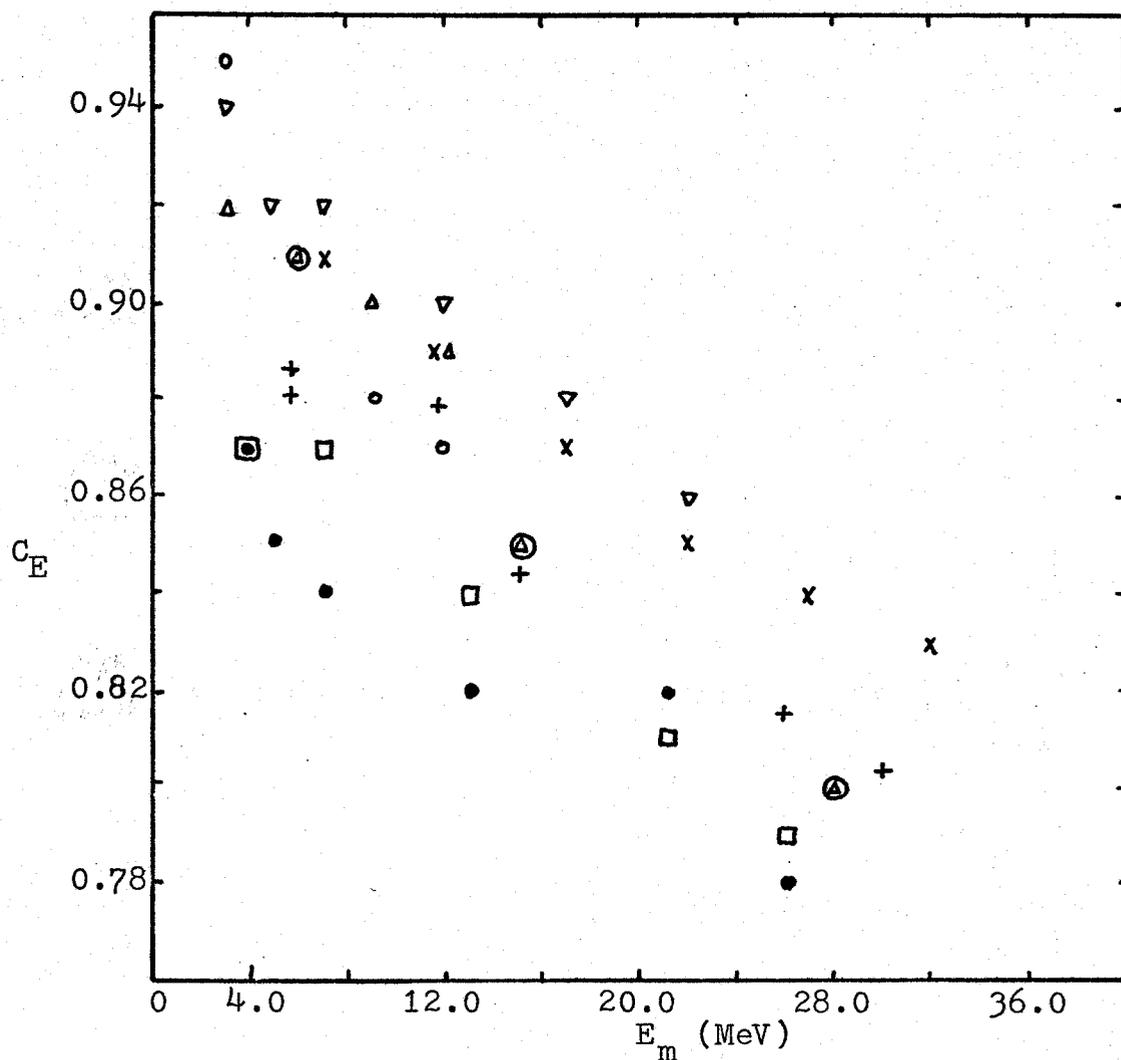


Figure 7. C_E vs Mean Electron Energy at the point of measurement. (▽) Kartha and MacDonald 1970 using Victoreen, (x) Kartha and MacDonald using Baldwin-Farmer, (△) Almond 1970 using Baldwin-Farmer, (○) Svensson and Petterson 1967 using Seimens, (+) Wambersie et al. using Baldwin, (●) present study using Capintec 1098, (□) present study using PTW 161244.

by other groups. Since not all measurements were made at the same depth in the same phantom material, the absorbed dose conversion factor is plotted as a function of the mean electron energy at the point of measurement

$$E_m = E_o (1 - (d/R_p)) \quad \text{Eqn. 22.}$$

where E_o is the incident electron energy and R_p is the projected range of the electron, $R_p = 0.52 \cdot E_o - 0.26$ for water (Svensson and Petterson 1967).

As can be seen from the Figure, the present results fall below those measured by other groups in all cases. Part of the discrepancy, however, is due to the differences in the G value for Fricke dosimetry used in each of the studies. The G values for each case are given in Table XII. The G value used in the present study was chosen on the basis of recommendations made in ICRU 21 (1972).

If the data in Figure 7 are normalized to a common G value, the spread in the data is seen to be reduced. While the present results still fall somewhat below the other data, they are well within the uncertainty associated with each point.

Recent data for 8 and 14 MeV electrons presented by Pitchford and Bidmead (1978) has not been included in the comparison. Insufficient data was presented in the paper to allow a comparison to be made.

Table XII
G Values Used in Figure 7

| Reference | G (per 100 eV) |
|-----------------------------|----------------|
| Wambersie et al. 1971 | 15.5 |
| Svensson and Petterson 1967 | 15.56 |
| Kartha and MacDonald 1970 | 15.5 |
| Almond 1970 | 15.56 |
| Present Study | 15.7* |

* This value has not been corrected for the normalization to the NRC calibration of the Capintec 1098 and PTW 161244. See Section 3.4.

6.4 C_{λ} Measurements

Measurements of C_{λ} , the absorbed dose conversion factor, for 25 MV x-rays and ^{60}Co gamma rays were conducted according to procedures described in Section 5.2 and the data analysed as described in Section 5.3. The results of these measurements for each of the ionization chambers studied are given in Table XIII.

As can be seen, the results are in excellent agreement with ICRU 14 (1969) and amongst themselves.

These results would disagree with the contention of Nahum and Greening (1976) and others that the present discrepancy between C_E and C_{λ} is a result of an error in the recommended C_{λ} values.

Table XIII
Measured C_{λ} Values

| Radiation Quality | Capintec 1098 | BF 533702 | PTW 161244 | ICRU 14 |
|----------------------|----------------------|---------------------|---------------------|---------|
| ^{60}Co | 0.95 ^{(4)*} | 0.94 ⁽⁵⁾ | 0.94 ⁽³⁾ | 0.95 |
| 25MV | 0.90 ⁽⁴⁾ | 0.88 ⁽⁴⁾ | 0.89 ⁽⁴⁾ | 0.90 |

* The number in brackets is the number of measurements from which the average value presented was determined.

7. CONCLUSIONS

On the basis of the results of the present study, it is possible to draw a number of conclusions.

The first deals with the phantom material to be used when making measurements using ionization chambers and/or Fricke dosimeters. The present study failed to find any significant difference between results obtained in lucite and those obtained in water for the radiation qualities studied. It would therefore appear to be possible to confidently use the simpler lucite system in routine measurements. It would, however, seem advisable to periodically refer back to the water system as a primary standard.

The second conclusion is that concerning the sleeves or buildup caps used with the various chambers. For the chambers and radiation qualities investigated, no observable effect of sleeve was determined. It would therefore seem possible to use whatever sleeve is best suited to the measurement being made.

The values of C_E measured in this study were found to be consistently of the order of 3% lower than the values recommended by ICRU 21 (1972). On the basis of these, one might conclude that either the values of C_E or of G or of some combination of the two values recommended in that report are in error.

The disagreement between the present results and those recommended by the ICRU was not, however, of sufficient magnitude that one would recommend changing the ICRU values, as has been suggested by some authors (See Table I). The recommended values would appear to introduce an error of no more than three percent to ionization chamber dosimetry. Although this is not insignificant, it does not justify discarding the standardization of dosimetry introduced by the recommendations.

Furthermore, this 3% may be one of the lesser sources of error when one is trying to determine the absorbed dose for low energy electrons using ionization chamber techniques. As pointed out in previous chapters, for these qualities factors such as depth-dose characteristics can introduce significant uncertainty in the measured value of the apparent exposure.

The final point to be made concerns the absorbed dose conversion factors for x- or gamma-radiation. The present results were found to be in excellent agreement with the recommendations of ICRU 14 (1969); contrary to theoretical predictions of Nahum and Greening (1976) and others. While this study is by no means exhaustive in terms of the chambers or radiation qualities studied, it would argue strongly against making any changes in the values recommended by ICRU 14 before a more thorough investigation has been conducted.

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