The development of new devices for accurate radiation dose measurement

A guarded liquid ionization chamber and an electron sealed water calorimeter

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Dedicated to the Glory of God and in loving memory of my great- uncle, Bill Jacobson and my grandfather, Jack Stewart 1916-2006

O eternal God, the fountain of all wisdom, pour out Your Holy Spirit upon us and enlighten us with Your grace, and so rule our minds, and guide our councils, that in all things we may seek Your will and Your glory, through Jesus Christ our Lord. Amen.

-a prayer of the Anglican Church of Canada

Abstract

In this work we developed two new devices that aim to improve the accuracy of relative and reference dosimetry for radiation therapy: a guarded liquid ionization chamber (GLIC) and an electron sealed water (ESW) calorimeter. With the GLIC we aimed to develop a perturbation-free energy-independent detector with high spatial resolution for relative dosimetry. We achieved sufficient stability for short-term measurements using the GLIC-03, which has a sensitive volume of approximately 2 mm³. We evaluated ion recombination in pulsed photon beams using a theoretical model and also determined a new empirical method to correct for relative differences in general recombination which could be used in cases where the theoretical model was not applicable. The energy dependence of the GLIC-03 was 1.1% between 6 and 18 MV photon beams. Measurements in the build-up region of an 18 MV beam indicated that this detector produces minimal perturbation to the radiation field and confirmed the validity of the empirical recombination correction. The ESW calorimeter was designed to directly measure absorbed dose to water in clinical electron beams. We obtained reproducible measurements for 6 to 20 MeV beams. We determined corrections for perturbations to the radiation field caused by the glass calorimeter vessel and for conductive heat transfer due to the dose gradient and non-water materials. The overall uncertainty on the ESW calorimeter dose was 0.5% for the 9 to 20 MeV beams and 1.0% for 6 MeV, showing for the first time that the development of a water-calorimeter-based standard for electron beams over a wide range of energies is feasible. Comparison between measurements with the ESW calorimeter and the NRC photon beam standard calorimeter in a 6 MeV beam revealed a discrepancy of $0.7\pm0.2\%$ which is still under investigation. Absorbeddose beam quality conversion factors in electron beams were measured using the ESW calorimeter for the Exradin A12 and PTW Roos ionization chambers. Differences of up to 1.2% were found compared with factors in the TG-51 protocol, which are based on calculations. This is the first time that water calorimetry has been used to measure beam quality conversion factors over a wide range of electron beam energies.

Résumé

Dans ce travail nous avons développé deux nouveaux détecteurs qui visent à améliorer l'exactitude de la dosimétrie relative et de référence en radiothérapie: une chambre d'ionisation liquide gardée (GLIC) et un calorimètre d'eau scellé pour les électrons (ESW). Avec la GLIC nous avons visé à développer un détecteur indépendant de l'énergie et libre de perturbations avec une résolution spatiale élevée pour la dosimétrie relative. Nous avons atteint une stabilité suffisante pour des mesures à court terme en utilisant la GLIC-03, qui a un volume sensible d'approximativement 2 mm³. Nous avons évalué la recombinaison générale des ions dans des faisceaux de photons pulsés en utilisant un modèle théorique et nous avons également déterminé une nouvelle méthode empirique, permettrant de corriger pour les différences relatives de recombinaison générale, qui pourrait être employée dans les cas où le modèle théorique ne serait pas applicable. La dépendance d'énergie du GLIC-03 était 1.1% dans des faisceaux de photon entre 6 et 18 MV. Les mesures dans la région de déséquilibre électronique ('build-up') d'un faisceau du 18 MV ont indiqué que ce détecteur introduit une perturbation minimale du champ de rayonnement et ont confirmé la validité de la correction empirique de recombinaison. Le calorimètre ESW a été concu pour mesurer directement la dose absorbée dans les faisceaux d'électrons cliniques. Nous avons obtenu des mesures reproductibles pour des faisceaux de 6 à 20 MeV. Nous avons déterminé les corrections nécessaires pour tenir compte des perturbations du champ de rayonnement introduites par le récipient de verre du calorimètre et du transfert thermique de conduction dû au gradient de dose et au fait que les matériaux ne sont pas de l'eau. L'incertitude globale sur la dose pour le calorimètre ESW était 0.5% pour les faisceaux de 9 à 20 MeV et 1.0% pour 6 MeV, prouvant pour la première fois que le développement d'une norme basée sur un calorimètre d'eau pour des faisceaux d'électrons pour un éventail d'énergies est faisable. La comparaison entre les mesures avec le calorimètre ESW et le calorimètre standard pour le faisceau de photon du NRC dans un faisceau de 6 MeV a indiqué une anomalie de $0.7\pm0.2\%$ qui est toujours à l'étude. Les facteurs de conversion permettant de déterminer la dose absorbée dans des faisceaux d'électrons de différentes qualités ont été mesurés en utilisant le calorimètre ESW pour les chambres d'ionisation Exradin A12 et PTW Roos. Des différences jusqu'à 1.2% ont été trouvées comparé aux facteurs proposés dans le protocole TG-51, basés sur des calculs. Ceci représente la première fois qu'un calorimètre d'eau est employé pour mesurer des facteurs de conversion pour la qualité de faisceau sur un éventail d'énergies de faisceaux d'électrons.

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Chapter 1

Introduction

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1.1 THE ROLE OF RADIATION THERAPY IN THE TREATMENT OF CANCER

Cancer is currently the leading cause of premature death in Canada, representing 32% of the potential years of life lost from all causes of death¹. It is estimated that 38% of Canadian women and 44% of men will be diagnosed with some type of cancer during their lifetime¹. Due to advances in cancer prevention, detection and treatment, however, the overall age standardized mortality rate due to cancer is decreasing¹.

Radiation therapy, along with surgery and chemotherapy, is one of the primary modalities used to treat cancer. The use of megavoltage radiotherapy beginning in the late 1950's has played a significant role in improving survival rates for many cancers². The aim of radiotherapy is to cure and/or relieve symptoms of the disease by delivering a dose of radiation to a well-defined target volume while

minimizing the dose to critical structures in order to reduce the probability of normal tissue complications.

1.2 ACCURACY IN RADIATION DOSE DELIVERY

Radiation dose is defined as the amount of energy absorbed per unit mass of an irradiated medium³. Several examples have been reported where a 7% change in radiation dose was clinically detectable in terms of patient outcome² (e.g. survival or complication rate) and, based on radiation dose response curves for tumor and normal tissues, it is recognized that a 5% change in dose could result in a 10 to 20% change in tissue response². Such strong changes in dose response require a high accuracy of radiation dose delivery.

There are four primary stages involved in determining the accuracy of radiation dose delivery. These are listed in Table 1.1 along with the currently achievable and recommended accuracies. In order to achieve the recommended 5% overall accuracy in delivery⁴, the accuracy of each stage must be 2.5%. Currently achievable accuracies at each stage range from 2 to 5% depending on the case.

		Current accuracy	Recommended accuracy
Stage 1	Absorbed dose to a reference point in water under reference conditions	2.5 - 5.0 %	2.5 %
Stage 2	Relative dose measurements at other points and for other conditions	2.0 - 3.3 %	2.5 %
Stage 3	Dose calculations for patient treatment planning	2.2 - 4.4 %	2.5 %
Stage 4	Patient irradiation	2.1 - 4.0 %	2.5 %
	Overall	4.4 - 8.4 %	5.0 %

Table 1.1 Current and recommended accuracy levels for the different stages involved in delivery of radiation dose to a patient (Ref. 2).

1.3 IMPROVING ACCURACY

There is current research being done to improve the accuracy of each stage in the radiation therapy process. In order to improve the patient irradiation stage, new techniques such as IMRT (intensity modulated radiation therapy) improve the conformality of the dose to the target volume by using small overlapping field segments to modulate the intensity across the field. Image guided radiation therapy (IGRT) uses imaging information obtained during treatment to confirm the location of the target volume within the patient and adjust the treatment for motion of the target within the patient. There continue to be many advances in radiation therapy treatment planning which improve the accuracy of Stage 3. These include Monte Carlo-based treatment planning systems, which can more accurately simulate the radiation dose deposition in a patient. Improving the accuracy of Stage 2 primarily relies on developing improved detector systems to provide better spatial resolution and less energy dependence. One example is radiochromic film which, since it is a film, has a very high 2-dimensional spatial resolution and has much lower energy dependence for megavoltage beams than traditional radiographic film. Finally,

improvement of Stage 1, the accuracy of the absorbed dose to water at the reference point (known as clinical reference dosimetry), depends on advances in national and international dosimetry standards and clinical reference dosimetry protocols. The introduction of absorbed dose to water-based standards and protocols has been an advance in this area. These protocols and standards will be discussed in more detail in sections 2.5 and 7.2, respectively.

1.4 HYPOTHESES

The focus of this work is on improving the accuracy of radiotherapy treatment delivery through improvements in the first two stages: reference dosimetry and relative dose measurements. We hypothesize that the development of two new devices for radiation dose measurements will improve the accuracy of radiation dose determination.

1. A guarded liquid ionization chamber (GLIC) will provide high-resolution energy-independent and perturbation-free dose information for relative dosimetry.

For relative dosimetry there is a need for detectors with high spatial resolution. This is particularly true for the relative measurements needed for IMRT treatment dosimetry, since these involve many small overlapping field segments. The dose distributions from such treatments can have steep gradients, making high resolution important. Since water is used as a reference medium for radiation dosimetry, a detector with radiation properties similar to water is important both to reduce perturbations to the radiation field and to decrease energy dependence. One region where these effects are particularly noticeable is at field edges, so again IMRT dosimetry would benefit from a water-equivalent detector. Besides IMRT, a detector with low perturbation and energy dependence and high spatial resolution would be useful for measurements in small radiation fields used for stereotactic radiosurgery, measurements in the build-up region of photon beams, and electron beam measurements.

2. Accurate absolute dosimetry for clinical electron beams can be performed using an electron sealed water (ESW) calorimeter.

There are currently large uncertainties on the determination of absorbed dose to water at a reference point for electron beams, the first step in determining the dose delivered to a patient. There are two reasons for this. The first is that most current absorbed dose standards are for ⁶⁰Co or high-energy photon beams. There are newly-developed graphite-calorimeter and ferrous-sulphate (Fricke) systems which determine absorbed dose to water for electron beams, but these systems require procedures to convert the absorbed dose in the detector medium (graphite or ferrous-sulphate) to absorbed dose to water. Water calorimetry would be the ideal system for measuring absorbed dose to water since no conversion procedure is required. However, although water calorimetry standards have been established for photon beams, they are not currently used for electron beams.

The second issue relates to the protocols for clinical reference dosimetry. These currently rely on calibration of ionization chambers in terms of absorbed dose to water in a ⁶⁰Co beam. In order to determine the absorbed dose in other beams, an absorbed dose beam quality conversion factor is necessary. For photon beams, the factors given for various chamber types have been verified using water calorimetry measurements. This is not the case for electron beams, and recent measurements and Monte Carlo simulations have indicated that there may be significant discrepancies between values given in protocols and actual values for certain chamber types. Water calorimetry could be used to directly measure these conversion factors in electron beams, thus providing more reliable data for future clinical reference dosimetry protocols.

1.5 OBJECTIVES

There are two main objectives of this work, both with the ultimate aim of improving the accuracy of radiation dose determination.

1. Develop and test the properties of a guarded liquid ionization chamber (GLIC). This involves determining an appropriate design and materials by constructing chamber prototypes and testing the short- and long-term stability of the chamber response. As well, ion recombination in the liquid must be studied and an appropriate method must be devised to correct for recombination effects. The energy dependence of the GLIC will be evaluated. Finally, GLIC measurements will be compared with measurements taken with other detectors to evaluate the accuracy of the recombination correction and to examine perturbation effects.

2. Develop the ESW (electron sealed water) calorimeter and use it for absolute determination of absorbed dose in clinical electron beams. This involves designing and constructing the ESW calorimeter for use in clinical electron beams and properly calibrating its components. As well, corrections for perturbations caused by non-water materials and conductive heat transfer must be accurately determined for each electron beam energy. To confirm the accuracy of the ESW calorimeter system, comparisons will be made in high-energy photon beams with the existing water calorimetry standard at NRC (National Research Council, Ottawa). Finally the ESW calorimeter will be used to directly measure beam quality conversion factors for ionization chambers in electron beams

1.6 ORGANIZATION OF THIS THESIS

Chapter 2 of this thesis provides some background information about radiation dosimetry and Appendix I provides a list of abbreviations commonly used in this thesis. These will serve as a reference for the remaining chapters of the thesis. Following Chapter 2, the thesis is divided into two main sections: Chapters 3 to 6 relate to the GLIC and Chapters 7 to 11 relate to the ESW calorimeter. Each section contains an introduction reviewing the relevant literature, materials and methods, results and discussion and a chapter with the conclusions and recommendations for future work and Chapter 12 gives a summary of the conclusions for both sections.

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Chapter 2

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2.1 BASIC DOSIMETRY CONCEPTS

2.1.1 Absorbed dose

The absorbed dose is related to the mean energy $\overline{\epsilon}$ imparted by ionizing radiation to matter of mass *m* in a finite volume *V* by¹:

$$D = \frac{d\overline{\epsilon}}{dm}.$$
 (2.1)

The energy imparted, ϵ , is found by taking the sum of all energy entering the volume and subtracting all energy leaving the volume, taking into account any

mass energy conversion within the volume. The special SI unit defined for dose is the gray (Gy), where 1 Gy = 1 J/kg.

2.2 THE DEPTH-DOSE CURVE

The variation of the dose with depth in a medium on the central axis is most commonly expressed as the PDD or percent depth dose, which is normalized to 100% at the point of maximum dose. This depth is referred to as d_{max} .

2.2.1 Photon beams

An example of a typical PDD in photon beams is shown in Figure 2.1. A noticeable feature of this curve is that it exhibits a build-up region near the surface. Dose is deposited by electron interactions, and in indirectly ionizing radiation, such as photon beams, the secondary electrons produced by photon interactions in the medium will travel a certain distance over which they will deposit energy. In megavoltage photon beams, the electrons are primarily forward directed and will travel into the medium a distance that increases with the beam energy. Therefore, near the surface, the electron fluence is lower, but it increases with depth and is maximum at the depth of d_{max} . At d_{max} , an equilibrium is reached, where the number and energy of electrons entering a volume is equal to the number and energy of electrons exiting that same volume, a condition known as charged particle equilibrium (CPE). Since the photon fluence decreases with depth due to attenuation, beyond d_{max} the number and energy of electrons entering a volume is not exactly equal to the number and energy that exit, but there remains a condition of transient charged particle equilibrium (TCPE), where the absorbed dose is proportional to the kinetic energy per unit mass released through photon interactions.



Figure 2.1 An 18 MV photon beam depth-dose distribution showing the build-up region and d_{max} .

2.2.2 Electron beams

A typical depth-dose curve for electron beams is shown in Figure 2.2. The major features of the electron PDD are a broad maximum region around d_{max} followed by a steep drop in absorbed dose and a low-dose tail due to bremsstrahlung radiation. The figure also shows, R_{p} , the practical electron range, and R_{50} , the depth at which the absorbed dose is 50% of the maximum.



Figure 2.2. A 6 MeV electron beam depth-dose distribution in water showing the parameters d_{max} , R_{50} and R_{p} .

2.3 IONIZATION CHAMBERS

An ionization chamber system consists of a chamber with three electrodes: a collecting electrode, guard electrode and outer electrode, as well as an electrometer and a power supply. The electrical arrangement of these components is shown in Figure 2.3 for the two most common geometrical configurations, plane-parallel (parallel plate) and cylindrical (thimble).

The electric field between the polarizing and collecting electrodes defines the sensitive volume of the chamber cavity. Positive and negative ions formed in this volume are attracted to the oppositely polarized electrodes and the collected charge is measured by the electrometer. The guard electrode is at the same potential as the collecting electrode. It prevents the measurement of leakage currents through the insulating materials and defines the sensitive volume. In plane-parallel chambers it also reduces the fluence perturbation effects for electron beams, as will be described in section 2.4.2.

Several properties such as the outer wall material and thickness, central electrode material and cavity dimensions are given in Table 2.1 for the commercial ionization chambers we have used in this work.

2.3.1 Corrections to the chamber reading

2.3.1.1 Correction for pressure, temperature and humidity

If the chamber is vented to the atmosphere, the mass of air inside the chamber will depend on the temperature and pressure of the environment according to the ideal gas relationship:

$$n = \frac{PV}{RT},$$
(2.2)

where n is the number of moles of air in the volume, P is the pressure, V is the chamber volume, R is the ideal gas constant and T is the temperature. The charge collected during irradiation is proportional to the mass of air in the chamber.

Reference conditions have been defined so that the chamber reading can always be referred to the same mass of air in the cavity. In North America, the reference conditions are $P_0 = 101.33$ kPa and $T_0 = 22^{\circ}C = 295.2$ K. The pressuretemperature correction factor is therefore:

$$p_{\rm TP} = \frac{P_0}{P} \frac{T}{T_0} = \frac{101.33}{P(\rm kPa)} \times \frac{T(^{\circ}\rm C) + 273.2}{295.2}.$$
 (2.3)

A humidity correction factor is generally not used since, as long as the chamber is used in a relative humidity between 20% and 80%, the effect of variations in humidity is negligible.

2.3.1.2 Correction for polarity effects

Electrons produced during irradiation can have various effects on the collecting electrode, stem, or cable of the ionization chamber that may lead to currents affecting the measured signal. Many of these currents, since they are caused by direct interaction of electrons with the chamber components, will have the same sign irrespective of the polarization of the chamber, so that most of these spurious

signals can be corrected for by taking measurements at both polarities. The correction for the polarity effect is:

$$p_{\rm pol} = \left| \frac{\left(M_+ - M_- \right)}{2M} \right|,$$
 (2.4)

where M_+ and M_- are the measurements taken with positive and negative polarities, respectively, and M is the measurement taken with the polarity that is used for calibration (either M_+ or M_-).

2.3.1.3 Correction for ion recombination

The number of ions created within an ionization chamber is directly related to the dose deposited in the chamber volume. However, not all of these ions are collected by the measuring electrode. Three effects contribute to this loss of charge: initial recombination, general recombination, and ionic diffusion against the electric field. Recombination corrections will be discussed in more detail in section 3.3.3.

2.3.1.4 Correction for leakage current

Leakage current is the signal measured by the electrometer when the polarizing voltage is applied to the chamber without irradiation. This current should be compared with the signal during irradiation and a correction should be applied if the leakage current is greater than 0.1% of the irradiation current.





Figure 2.3. Schematic diagram of ionization chamber circuitry for a typical (a) plane-parallel and (b) cylindrical chamber.

Table 2.1 Characteristics of commercial ionization chambers used in this work

Cylindrical chambers	Cavity volume (cm ³)	Cavity radius (mm)	Wall material	Wall thickness (g/cm ²)	Central electrode material	Waterproof
Exradin A12	0.65	3.1	C552	0.088	C552	Yes
NE 2571	0.6	3.2	graphite	0.065	Aluminum	No
PTW 30013		3.1	graphited PMMA	0.057	Aluminum	Yes
Plane-parallel chambers	Electrode spacing (mm)	Collecting electrode diameter (mm)	Wall material	Wall thickness (g/cm ²)	Guard ring width (mm)	Waterproof
Exradin A14P	1	1.5	C552	0.176	0.5	Yes
PTW Roos	2	16	graphited PMMA	0.118	4	Yes

2.4 CAVITY THEORY

A dosimeter will always register a reading that relates to the dose in its own medium, not the medium in which it is placed. The reading from an air-filled ionization chamber will be related to the dose to the air inside the chamber:

$$D_{\rm air} = \frac{Q_{\rm air}}{m_{\rm air}} \left(\frac{W_{\rm air}}{e}\right),\tag{2.5}$$

where m_{air} is the mass of the air inside the chamber, Q_{air} is the charge produced and W_{air}/e is the average energy required to produce an ion pair in air normalized by the electron charge.

For specific conditions, the dose to the dosimeter material can be related to the dose that would have been deposited in the medium at that point if the dosimeter were not present. These relationships are based on cavity theory. Underlying cavity theory is the relationship between absorbed dose, D, and particle fluence, Φ :

$$D = \Phi\left(\frac{\overline{S}}{\rho}\right),\tag{2.6}$$

where $\left(\frac{\overline{s}}{\rho}\right)$ is the mean unrestricted mass collisional stopping power averaged over the spectrum of electrons. Equation (2.6) assumes that all radiative photons escape the volume of interest and that any secondary electrons created are absorbed on the spot. The second assumption does not hold in reality, but the result is still valid in regions of CPE since secondary electrons escaping the region are replaced by others entering. The dose in medium m_1 can be related to the dose in a second medium m_2 , by:

$$\frac{D_{m_1}}{D_{m_2}} = \frac{\left(\frac{\overline{S}}{\rho}\right)_{m_1} \Phi_{m_1}}{\left(\frac{\overline{S}}{\rho}\right)_{m_2} \Phi_{m_2}}.$$
(2.7)

In order for this relationship to be valid, CPE must exist in each medium.

Bragg² and Gray³ developed the Bragg-Gray cavity theory to deal with the problem of relating the absorbed dose in a detector inserted into a medium to that in the medium itself. Spence and Attix⁴ generalized this cavity theory to allow for the creation of secondary electrons and Nahum⁵ further adapted the theory to correct for the energy deposited at the end of the electron tracks. For cavity theory to hold, the two Bragg-Gray conditions must first be met.

- 1. The cavity is small when compared with the range of charged particles incident on it so that its presence does not perturb the fluence of charged particles in the medium.
- 2. The absorbed dose in the cavity is deposited solely by charged particles crossing it.

The result of the first condition is that the fluences in equation (2.7) are the same and equal to the equilibrium fluence established in the surrounding medium. The second condition implies that all electrons, depositing dose inside the cavity, are produced outside of and completely cross the cavity, therefore no secondary electrons are produced inside the cavity and no electrons stop within the cavity. This, of course, is only valid in regions of CPE or TCPE. Since the fluence in the medium Φ_m and the fluence in the cavity Φ_c are the same when the two conditions are met, the dose to the medium is related to the dose to the cavity by:

$$\frac{D_m}{D_c} = \frac{\overline{s}_m \Phi_m}{\overline{s}_c \Phi_c} = \overline{s}_{m,c} , \qquad (2.8)$$

where $\overline{s}_{m,c}$ is the restricted mass collision stopping power ratio medium/cavity, calculated using the Spencer-Atix formulation with the Nahum track-end terms. In reality, the presence of a cavity always causes some degree of fluence perturbation, which is corrected for as described in the following sections.

As it is based on the range of electrons in the cavity medium, the fulfillment of the Bragg-Gray conditions will depend on the cavity size, cavity medium, and electron energy. A cavity which qualifies as a Bragg-Gray cavity for high energy

photon beams, for example, may not behave as a Bragg-Gray cavity in a mediumor low-energy x-ray beam.

2.4.1 Wall and central electrode perturbation correction factors p_{wall} and p_{cel}

The introduction of other materials for the wall and central electrode of an ionization chamber causes a perturbation to the electron spectrum inside the cavity. Although analytical methods can be used in photon beams to estimate the corrections necessary for this effect, p_{wall} and p_{cel} , these methods do not generally produce correct values of p_{wall} for plane-parallel chambers. Therefore measurements or Monte Carlo simulations are used. In electron beams these corrections were thought to be unity, but more recent results show that this assumption may be incorrect. This will be discussed further in section 7.5.

2.4.2 Fluence perturbation correction factor $p_{\rm fl}$

The fluence correction factor p_{fl} accounts for perturbations of the electron fluence in the medium due to the cavity. For photon beams where CPE or TCPE exists, there is no fluence perturbation caused by the cavity if the atomic numbers of the medium and the cavity are similar (as they are between water and air, for example). In this case Fano's theorem can be applied which states, "In a medium of given composition exposed to a uniform flux of primary radiation, the flux of secondary radiation is also uniform and *independent of the density* [*sic*] for the medium as well as of the density variations from point to point."⁶ However, this is not applicable in regions where CPE does not exist such as the build-up region or field edge.

In electron beams the fluence is affected by the presence of a low-density cavity in a higher density medium through two competing effects: in-scattering and obliquity (see Figure 2.4). In-scattering increases the fluence within the cavity because fewer electrons are scattered out of the cavity than are scattered in by the medium. The obliquity effect is caused by the fact that electrons tend to travel in straighter paths in the cavity due to decreased scattering. They therefore have shorter path-lengths than they would in the medium, which results in a decrease in the fluence. In-scattering is the dominant effect and becomes especially important at low electron energies. In plane-parallel chambers the contribution to the measured signal due to in-scattering can be minimized by using a guard ring around the measuring electrode that is thick enough to collect all ions produced by in-scattered electrons.



(a) In-scattering

(b) Obliquity

Figure 2.4. Schematic diagram showing effects of in-scattering (a) and obliquity (b) on ionization chamber response for electron beams. Solid lines represent the electron tracks with the cavity present. Dashed lines represent electron tracks in the absence of the cavity.

2.4.3 Gradient correction factor $p_{\rm gr}$

A detector has a finite size and will represent the dose at a representative or "effective" point. An effect of inserting a cavity into a medium is that this "effective point of measurement" does not coincide with the cavity center. Since, in general, we have a gas-filled cavity in a medium of higher density, the electron fluence in the cavity is representative of the fluence in the medium at some point closer to the source than the center of the cavity. There are two possible ways to account for this effect. One is to introduce a gradient correction that depends on

the cavity size and dose gradient. The other is to use the "effective point of measurement", where a point upstream of the center of the cavity is effectively the depth in the medium which corresponds to the electron fluence in the cavity. For cylindrical chambers in photon beams the shift is 0.6 r_{cav} , where r_{cav} is the radius of the camber cavity, and for electron beams the shift is 0.5 r_{cav} . For plane parallel chambers p_{gr} is unity as long as the point of measurement is taken as the inside surface of the front face of the chamber.

2.5 CLINICAL REFERENCE DOSIMETRY PROTOCOLS

Clinical reference dosimetry protocols provide a consistent method for determining the absorbed dose to water under specific reference conditions. The calibration of the output of a linear accelerator or ⁶⁰Co beam is referred to as clinical reference dosimetry. Reference dosimetry is important because all other dosimetry used in prescribing patient treatment refers back to this dose output calibration.

All calibration protocols make use of ionization chambers. These chambers have calibration factors that are generally determined in a ⁶⁰Co beam and are traceable to a national primary standards laboratory. The chamber may be calibrated directly at the standards laboratory or cross-calibrated with another ionization chamber for which the calibration factor has already been established.

Currently the main clinical reference dosimetry protocols used are TG-51 (Ref. 7) and TRS-398 (Ref. 8). These are absorbed dose-based protocols which use an absorbed dose to water calibration coefficient defined as:

$$N_{D_{w}} = \frac{D_{w}}{M} [\text{Gy/C}], \qquad (2.9)$$

where M is the corrected reading of the chamber in water and D_w is the dose to water at the point of measurement.

2.5.1 Beam quality specification

The quantities used in converting an ionization chamber reading into a measurement of absorbed dose depend not only on the chamber properties but also on the radiation beam type and energy. Since linear accelerator beams are not mono-energetic, there needs to be a way to quantify the average or dosimetrically effective energy of the beam. This specification is known as beam quality and is designated by Q.

2.5.1.1 Photon beams

Two beam quality specifiers are used in radiation dosimetry protocols: TPR_{10}^{20} and $%dd(10)_x$. TPR²⁰₁₀ is used by the IAEA TRS-398 protocol. TPR stands for tissue-phantom-ratio and TPR_{10}^{20} is the ratio of the dose at 20 cm depth to the dose at 10 cm depth for a constant source-detector distance (SAD) and a field size of 10×10 cm² defined in the plane of the detector (see Figure 2.5). The TG-51 protocol uses the quantity $%dd(10)_{x}$ to define beam quality. This is the percent depth dose at 10 cm depth compared to the dose at the depth of maximum dose for a field size of 10×10 cm² at the phantom surface and a source-surface distance (SSD) of 100 cm (see Figure 2.5), where the dose due to contaminating electrons formed in the linear accelerator head has been corrected for. In order to correct for the effect of electrons in the photon beam, a 1 mm Pb filter is added to remove electron contamination from the head. This filter introduces a known electron contamination that can be corrected for to determine $%dd(10)_{x}$. Most clinical beams are accurately specified by TPR_{10}^{20} , however, this specification is not adequate for certain filter and target combinations, such as those in some experimental accelerators used in standards labs. $%dd(10)_{x}$ provides a unique specifier for both clinical and experimental beams.


Figure 2.5. Diagram showing the setup for (a) SSD (source-surface distance) configuration and (b) SAD (source-axis distance) configuration. d is the depth in the phantom of the point of measurement of the chamber.

2.5.1.2 Electron beams

The beam quality specifier used for electron beams is R_{50} . This is the depth on the central axis at which the dose is 50% of the maximum dose. There are two methods to determine R_{50} . Since the average electron energy will vary with depth, one option is to use a detector with little energy dependence over the range of electron energies present, such as a silicon diode. Another option is to convert the ionization, measured using an ionization chamber, into dose. Ding et al.⁹ used Monte Carlo simulations to derive an expression relating I_{50} , the depth at which the ionization is 50% of its maximum value, to R_{50} :

$$R_{50} = 1.029 I_{50} - 0.063 [\text{cm}]. \qquad (2.10)$$

Monte Carlo simulations of realistic electron beams¹⁰ provide a single direct relationship between R_{50} and $\overline{s}_{w,air}$ if the measurements are taken at a reference depth d_{ref} where:

$$d_{ref} = 0.6 R_{50} - 0.1 [\text{cm}]. \tag{2.11}$$

In this case:

$$\overline{s}_{w,air}\left(d_{ref}\right) = 1.2534 - 0.1487 \left(R_{50}\right)^{0.2144}.$$
(2.12)

The AAPM TG-51 and IAEA TRS-398 protocols both use this relationship. There is also a more general expression relating $\overline{s}_{w,air}$ to R_{50} at any depth z (Ref. 10).

2.6 BEAM QUALITY CONVERSION FACTORS

TG-51 and TRS-398, are formulated for ionization chambers calibrated in terms of absorbed dose to water in 60 Co, although both also allow for calibration at other beam qualities. Cavity theory must therefore be used when establishing absorbed dose to water in other beams. Using the relationship between absorbed dose to air and absorbed dose to water according to equation (2.8):

$$N_{D_{\rm w}} = N_{D_{\rm air}} \overline{s}_{\rm w,air} p_{\rm wall} p_{\rm cel} p_{\rm fl} p_{\rm gr} \,. \tag{2.13}$$

Absorbed dose to water calibration coefficients in ⁶⁰Co, $N_{D_w}^{^{60}Co}$, are provided for ionization chambers by standards laboratories. The absorbed dose beam quality conversion factor k_Q is defined as:

$$k_{Q} = \frac{N_{D_{w}}^{Q}}{N_{D_{w}}^{^{60}C_{0}}}.$$
(2.14)

If the chamber is calibrated in terms of absorbed dose at both qualities, this equation is sufficient for evaluating k_Q . By application of equation (2.13) at both ⁶⁰Co and the quality Q and assuming that $(N_{D_{air}})_{60} = (N_{D_{air}})_Q$ (which implies that $(W_{air}/e)_{60} = (W_{air}/e)_Q$), k_Q can be evaluated as follows:

$$k_{Q} = \frac{\left[\overline{s}_{\text{w,air}} p_{\text{wall}} p_{\text{cel}} p_{\text{fl}} p_{\text{gr}}\right]_{Q}}{\left[\overline{s}_{\text{w,air}} p_{\text{wall}} p_{\text{cel}} p_{\text{fl}} p_{\text{gr}}\right]_{6^{0} \text{Co}}}.$$
(2.15)

The absorbed dose to water in a beam of quality Q can be calculated using the equation:

$$D_{w}^{Q} = k_{Q} M N_{D_{w}}^{60} C_{0} .$$
 (2.16)

This is the basic equation used in the TG-51 and TRS-398 protocols for both photon and electron beam calibration. For electron beams, TG-51 expands equation (2.16) as:

$$D_{w} = M N_{D,w}^{Co} k'_{R_{50}} k_{ecal} p_{gr}^{Q}.$$
(2.17)

 p_{gr}^Q is the gradient correction necessary for cylindrical chambers in TG-51 to account for the effective point of measurement as described in section 2.4.3. p_{gr}^Q is calculated by taking two measurements, one with the chamber center at d_{ref} and the second with the chamber center at $d_{ref} + 0.5 r_{cav}$, and using the equation:

$$p_{\rm gr}^{Q} = \frac{M\left(d_{\rm ref} + 0.5r_{\rm cav}\right)}{M\left(d_{\rm ref}\right)},$$
(2.18)

where r_{cav} is the radius of the chamber cavity. k_{ecal} is the beam quality conversion factor from ⁶⁰Co to an electron beam with an arbitrarily defined R_{50} of 7.5 cm. It is dependent on the chamber type and is given in the TG-51 protocol for many common chamber types. $k'_{R_{50}}$ is the beam quality conversion factor from an electron beam with $R_{50} = 7.5$ cm to the beam quality of interest. This factor is determined using the graphs or equations given in TG-51.

	TRS-398	TG-51
Beam quality range	$1 \text{ cm} \le R_{50} \le 20 \text{ cm}$	$2 \text{ cm} \le R_{50} \le 20 \text{ cm}$
Phantom material	$R_{50} \ge 4$ cm, water $R_{50} < 4$ cm, water or plastic with appropriate depth scaling	water
Chamber type	$R_{50} \ge 4$ cm, plane-parallel or cylindrical $R_{50} < 4$ cm, plane-parallel	$R_{50} > 4.3$ cm, plane-parallel or cylindrical $R_{50} \le 4.3$ cm, plane-parallel preferred $R_{50} \le 2.6$ cm, plane-parallel required
Depth	$d_{\rm ref} = 0.6 R_{50} - 0.1 [\rm cm]$	$d_{\rm ref} = 0.6 R_{50} - 0.1 \ [\rm cm]$
Chamber position	plane-parallel chambers, inner surface of front window at d_{ref} cylindrical chambers, center of cavity at $0.5r_{cav}$ deeper than d_{ref}	plane-parallel chambers, inner surface of front window at d_{ref} cylindrical chambers, center of cavity at d_{ref}
SSD	100 cm	90 to 110 cm
Field size at phantom surface	$10 \times 10 \text{ cm}^2$ or size used for output normalization, whichever is larger	$R_{50} \le 8.5$ cm, 10×10 cm ² or larger $R_{50} > 8.5$ cm, 20×20 cm ² or larger

Table 2.2. Reference conditions for the determination of absorbed dose in electronbeams given by the IAEA TRS-398 and AAPM TG-51 protocols.

2.6.1 Photon beam calibration

Photon beam calibration is done using a cylindrical ionization chamber with an $N_{D,w}^{Co}$ calibration coefficient traceable to a national primary standards laboratory. The chamber is positioned on the central axis of the beam with the center of the chamber at 10 cm depth in water (5 cm depth is allowed for ⁶⁰Co beams). The field size is 10×10 cm² and is defined on the surface of the phantom if an SSD setup is used, or in the plane of the detector if an SAD (source-axis distance) setup is used (see Figure 2.5). The SSD or SAD is chosen to be the normal clinical distance for the machine being calibrated. Chamber readings are

corrected as described in section 2.3.1. Beam quality is determined using TPR₁₀²⁰ (IAEA TRS-398) or %dd(10)_x (AAPM TG-51), as described in section 2.5.1.1. The k_Q values are tabulated in the protocols for most commonly used cylindrical chambers as a function of beam quality. The absorbed dose to water can then be calculated from the fully corrected chamber reading using equation (2.16).

2.6.2 Electron beam calibration

Electron beam measurements for the TRS-398 and TG-51 protocols are done according to the guidelines given in Table 2.2. Chamber readings are corrected as described in section 2.3.1. Beam quality is determined from R_{50} , which is measured as described in section 2.5.1.2.

The use of plane-parallel chambers is required in the protocols for the calibration of low-energy electron beams. If these chambers are calibrated in ⁶⁰Co beams, then their correction factors in ⁶⁰Co must be used in the determination of k_Q or k_{ecal} . This can cause problems because the correction factors at ⁶⁰Co are not well established for plane-parallel chambers and plane parallel chambers are less stable than cylindrical chambers. In order to avoid this difficulty, the protocols recommend that plane-parallel chambers be cross-calibrated in a high-energy electron beam against a calibrated cylindrical chamber. In the TG-51 formulation, the product of $N_{D_w}^{60}C_o k_{ecal}$ can then be calculated using:

$$\left(N_{D_{w}}^{^{60}Co}k_{ecal}\right)_{pp} = \frac{\left(D_{w}\right)_{cyl}}{\left(Mk_{R_{50}}'\right)_{pp}} = \frac{\left(MN_{D_{w}}^{^{60}Co}k_{R_{50}}'k_{ecal}p_{gr}^{Q}\right)_{cyl}}{\left(Mk_{R_{50}}'\right)_{pp}},$$
(2.19)

where the subscripts "pp" and "cyl" refer to the plane-parallel and cylindrical chambers, respectively. The TRS-398 protocol allows for a similar method of cross-calibration of plane-parallel chambers in electron beams.

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Chapter 3

Introduction to liquid ionization chambers

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3.1 AIR- VERSUS LIQUID-FILLED IONIZATION CHAMBERS

Air-filled ionization chambers are the most commonly used instrument for clinical radiation dose measurements. Their ease of use, exceptional long-term stability and well-studied characteristics make this the detector of choice for many dosimetry applications. However, there are some characteristics of air-filled chambers that limit their accuracy for certain measurements. First of all, because air is a low-density medium, the amount of ionization produced by radiation in an air-filled chamber is low. This becomes a problem for constructing chambers with very small volumes and therefore limits the size (and thereby the spatial resolution) of air-filled chambers. A second problem is that when measuring in a medium of higher density, such as water, the introduction of a low-density cavity perturbs the electron fluence within the medium, thus perturbation corrections are required to determine the dose in the absence of the cavity. Finally, because the ratio of the mean restricted collision mass stopping powers water-to-air varies

with electron energy by several percent over the range of energies used clinically, the conversion of ionization chamber response to absorbed dose to water is energy dependent. These effects become particularly important in regions requiring high resolution, in areas where charged particle equilibrium is not present, and in regions where the average electron energy varies or is unknown. Some examples are measurements in the build-up region for high-energy photon beams, profile measurements of very small radiation fields and measurements of IMRT fields.

Insulating liquids have been proposed for use in ionization chambers because they possess certain advantages compared with air-filled chambers. When measuring in a medium such as water, liquids produce negligible perturbation effects as their density is very similar to water. As well, for certain insulating liquids, the mean restricted collision mass stopping power ratio water-to-liquid shows only a very small variation with electron energy over the range of energies used clinically. Therefore a liquid-filled detector should have very little energy dependence. A further advantage of using liquids in ionization chambers is that liquids have an ionization density about 300 times that of air. This means that a liquid-filled chamber can have a much smaller size than a gas-filled chamber and still produce a sufficiently large signal, thus providing high spatial resolution.

Although liquid-filled ionization chambers possess many advantages, there are also some aspects that complicate their use. The first is the stability of the chamber response. This can be affected by impurities which can alter the background or leakage signal as well as changing the chamber response through radiation-induced chemical reactions. It is important, therefore, to monitor the chamber response to ensure reproducible and stable readings with minimal leakage signal. Care must also be taken when choosing the chamber materials to ensure that they will not react with the liquid or introduce impurities. The second factor that makes the use of liquid ionization chambers challenging is the high ion recombination rate in liquids. The high ionization density along with the low ion mobility in liquids increase the probability that ions will recombine before being collected. The effect of recombination must therefore be carefully corrected for. This will be discussed in more detail in section 3.3.3.2.

3.2 HISTORICAL OVERVIEW OF LIQUID IONIZATION CHAMBERS

In 1896, Thomson discovered that dielectric (also known as non-polar or insulating) liquids were ionized when irradiated with Röntgen (x-) rays¹. Jaffé studied the ionization of several non-polar liquids under irradiation with α and β -rays in the formulation of his theory of columnar ionization^{2,3}, a theory that is still used in describing ionization due to high LET radiation. Many further studies were undertaken to determine the properties of irradiated dielectric liquids⁴, such as ion mobility⁵ and free ion yield⁵⁻⁷. Development of liquid ionization chambers was spurred on primarily by the fields of nuclear and high energy physics, where these detectors found wide application, but there has been continued interest in using liquid ionization chambers in medical physics applications.

There are two major areas where liquid ionization chambers have been applied to medical physics. The first is the use of matrix ionization chambers as either portal imaging or beam monitoring devices. Portal images are patient images acquired using the megavoltage treatment beam from a linear accelerator with the patient in the treatment position and are used to verify the location of patient anatomy in relation to the radiation field before treatment. Detectors for portal imaging must be able to provide two-dimensional information at a sufficiently high resolution. Work has been done to develop and test a multi-wire matrix liquid ionization chamber as a portal imaging device for clinical linear accelerators⁸. There have also been investigations into the possibility of using these portal imaging devices for treatment verification dosimetry⁹⁻¹¹. This would involve measuring the transmitted radiation during patient treatment and using this information to reconstruct the dose delivered to the patient. Issues have been reported with these devices relating to dependence on the gantry angle¹² and other instabilities¹⁰ indicating that careful quality assurance procedures must be followed if this type of device is used for dose verification.

Two new devices similar to those used in portal imaging have recently been developed: one for quality assurance of IMRT plans before treatment^{13,14} and one for monitoring IMRT fields during treatment delivery¹⁵. Both of these devices are also composed of two-dimensional linear array liquid ionization chambers, and thus provide planar dose information. This is important for IMRT as the fields are highly non-uniform, so point detectors such as conventional ionization chambers do not provide sufficient information to verify that a treatment is delivered correctly.

The second area of development is applying liquid ionization chambers to clinical radiation dosimetry. Some studies have examined the use of liquid ionization chambers in mixed γ -ray and neutron dosimetry¹⁶⁻¹⁸. However, the most extensive work on the development of liquid ionization chambers for use in clinical dosimetry has been done by Wickman et al. ¹⁹⁻³³ and has focused on photon dosimetry. This group has constructed and tested many chamber designs and has also studied issues related to ion recombination in liquids which will be discussed in section 3.3.3.2. Other groups have also performed studies with commercial air ionization chambers filled with insulating liquids³⁴⁻³⁶.

We carried out some previous work with one of the Wickman chambers^{37,38}. As well, we tested an Exradin A14P chamber that had been modified to reduce the electrode separation to 0.5 mm and filled with isooctane³⁸⁻⁴¹. Although some of the characteristics of this chamber were not ideally suited for measurements when filled with liquids, it did provide us with insight into the operation of liquid ionization chambers which we made use of in our designs.

3.3 PROPERTIES OF DIELECTRIC LIQUIDS

3.3.1 Free ion yield

The process of liquid ionization by fast electrons is different from the direct single ionization process generally observed for low LET radiation in gases. Ionizations and excitations in liquids occur predominantly in spurs where about 100 eV are lost in the interaction generating clusters of two to three electron/ion pairs⁴². At the end of an electron track a region of higher ionization density, termed a blob, is formed. Additionally, unlike in gases, most electrons released through ionizing interactions remain at distances where they are still in the Coulomb field of their parent molecule and will tend to recombine with it. Those that escape this germinate recombination are termed free ions, so an important quantity for liquids is the yield of free ion pairs, or $G_{\rm fi}$. This is defined as the number of electron/ion pairs produced per 100 eV of absorbed energy that escape their mutual Coulomb attraction.

Onsager examined this escape process in his study of electrolytic dissociation⁴³ and applied his theory to dissociation produced by ionizing radiation⁴⁴. According to Onsager's theory, the probability of an electron escaping the Coulomb field, P_{esc} , can be expressed as a function of r, the initial separation and θ , the orientation of the pair with respect to the external electric field by the relationship:

$$P_{\rm esc}(r,\theta) = \exp\left(\frac{-r_c}{r} - \beta r (1 - \cos\theta)\right) \sum_{n,m=0}^{\infty} \frac{\beta^{n+m} (1 + \cos\theta)^{n+m} r^n r_c^m}{m!(m+n)!}, \quad (3.1)$$

where:

$$r_c = \frac{e^2}{\varepsilon k_{\rm B}T}$$
 and $\beta = \frac{eE}{2k_{\rm B}T}$. (3.2)

Here *e* is the electric charge, ε is the relative permittivity of the liquid, *E* is the external electric field strength, $k_{\rm B}$ is the Boltzman constant and *T* is the absolute temperature of the liquid. An integration of this expression over all initial angles θ , assuming isotropic distribution, was determined by Mozumder⁴⁵ and Terlecki

and Fiutak⁴⁶. The resulting $P_{esc}(r)$ can be combined with the initial distribution of electron separation, F(r) and integrated so that:

$$G_{\rm fi} = G_{\rm tot} \int_{0}^{\infty} F(r) P_{\rm esc}(r), \qquad (3.3)$$

where G_{tot} is the total number of electrons released per 100 eV absorbed energy. An interesting property of Onsager's escape probability is that the first expansion term is independent of *r* and varies linearly with *E*:

$$P_{\rm esc} = e^{-r_c/r} \left(1 + \frac{er_c}{2k_{\rm B}T} E + \dots \right).$$
(3.4)

So $G_{\rm fi}$ can be observed to increase linearly with electric field at low field strengths. However, at higher electric field strengths, typically on the order of 1 MV/m, higher order terms in the series become significant, so the variation with electric field strength becomes sub-linear⁴⁷. In order to compare the free ion yield of different liquids, a useful quantity is $G_{\rm fi}(0)$, the free ion yield at zero electric field strength. This is determined by measurements of ion collection as a function of electric field in the region where linear behavior is observed and then extrapolating to zero field strength.

3.3.2 Ion mobility

Another important property to consider in using liquids in ionization chambers is the mobility of the positive and negative ions created by ionization. The mobility, k, is expressed in units of m² V⁻¹ s⁻¹, so the transit time, τ , for ions to travel across the separation between electrodes, d, in an ionization chamber is determined by:

$$\tau = \frac{d}{kE} \,. \tag{3.5}$$

For pulsed radiation beams, the transit time is important in cases where we want to ensure that all ions created by one radiation pulse are collected before the arrival of the next pulse. Generally the mobilities of ionized liquids are on the order of 1000 times lower than those of gases, so this transit time can easily be of the same order as the pulse frequency for a linear accelerator, even with very small electrode separation and very high field strengths. The lower mobility also increases the probability for ion recombination, as will be discussed in the following section.

3.3.3 Ion recombination

In operating any ionization chamber, not all of the free ions produced will be collected. Three main effects contribute to this loss of charge: initial recombination, general recombination and diffusion. In initial recombination, oppositely charged ions produced along a single ionizing particle track recombine. The rate of initial recombination depends on the ionization density along a track, which will increase with the density of the ionized medium and with the LET of the ionizing particle. In general recombination, ions from different tracks will recombine. This depends on the density of ionizing particles in the medium, which is a function of the dose rate in continuous beams or the dose per pulse in pulsed beams. Both initial and general recombination also depend on the ion mobility. Charge loss due to diffusion against the electric field has a low probability of occurring and is generally considered negligible.

3.3.3.1 General recombination in air-filled chambers

For air-filled chambers measuring low LET radiation, initial recombination becomes negligible above a very low electric field strength (10^4 V/m). General recombination is therefore the dominant mechanism for ion loss. Examination of corrections for the ion loss due to general recombination in gases have been undertaken by Mie⁴⁸, Greening⁴⁹ and Boag⁵⁰⁻⁵². The most commonly used technique for determining the correction for ion recombination is the so-called two-voltage technique. This method is derived from Boag's theory of general recombination in gases. For gas-filled plane parallel chambers in pulsed radiation beams, the theoretical general collection efficiency, *f*, is given by:

$$f = \frac{1}{u} \ln(1+u), \qquad (3.6)$$

where:

$$u = \mu \frac{r_{\rm B}}{U} d^2, \qquad (3.7)$$

and:

$$\mu = \frac{\alpha}{e(k_+ + k_-)}.$$
(3.8)

In these equations, $r_{\rm B}$ is the initial charge density of positive or negative ions per radiation pulse, U is the applied potential, d is the electrode separation, k_+ and k_- are the mobilities of the positive and negative ions respectively, and α is the recombination rate constant for the gas (expressed in units of cm³/s). Correcting for this loss of charge is accomplished by multiplying by a factor $p_{\rm ion}$, which is the inverse of the collection efficiency.

There is also an alternative formulation of equation (3.6). With increasing electric field, gases exhibit a saturation of collected charge as demonstrated in Figure 3.1. In the region near saturation, the inverse of the charge collected is linearly related to the inverse of the applied voltage. In this region, if two measurements of the charge, Q_1 and Q_2 , are taken for equal times with different voltages, U_1 and U_2 , a "two voltage" equation for p_{ion} can be derived from equation (3.6):

$$p_{\rm ion}(Q_1) = \frac{1}{f} = \frac{Q}{Q_1} = \frac{1 - (U_1/U_2)}{(Q_1/Q_2) - (U_1/U_2)}.$$
(3.9)

This is the equation most often used in dosimetry protocols to correct for general recombination effects in ionization chambers.



Figure 3.1 Variation of the collection efficiency f of a gas-filled ionization chamber with applied potential, where Q' is the collected charge and Q is the actual charge produced by the radiation. As the potential increases, the ionization chamber approaches saturation where Q' = Q.

Several other assumptions are also made in this formulation. First, any effects of space-charge screening and diffusion loss have been neglected. It also assumes that the recombination during the radiation pulse is negligible (the pulse must be short compared to the ion transit time) and that the densities of ions of opposite charges are equal (all negative charge is carried by negative ions). Finally, the pulse repetition frequency must be low enough that the charge generated by a radiation pulse is fully collected before the next pulse occurs.

3.3.3.2 General recombination in liquid-filled ionization chambers

Determining ion recombination in liquids is not as straightforward as determining it in gases and the amount of recombination is much larger due to the high ionization density and low ion mobility in liquids. Equation (3.9) is not applicable as key conditions cannot be met. Charge collection in liquids does not saturate with increasing applied voltage due to the fact that increasing the voltage increases the number of free ions available in the volume, as discussed in section 3.3.1 As well, the effects of initial recombination are large in liquids even at very high electric field strengths, so it is not possible to operate in a region where initial recombination can be neglected. The condition that all charges from one radiation pulse must be collected before the next radiation pulse occurs can also be difficult to achieve in liquids, as their mobilities are much lower than gases.

Attempts have been made, however, to apply a modified form of Boag's theory to liquids. The model of Johansson et al. (Ref. 26) first examines the relationship between the measured current in pulsed radiation beams and the applied voltage in conditions of low dose per pulse (to minimize general recombination) and where the charge generated by one pulse is completely collected before the next pulse occurs. In this case, above a certain voltage, general recombination effects become negligible so the current can be observed to increase linearly with applied voltage as predicted by equation (3.4). Fitting a straight line to this region provides an expression for the theoretical current in the absence of recombination:

$$i_{\text{theor}} = (c_1 + c_2 E) D,$$
 (3.10)

where *E* is the electric field strength, \dot{D} is the dose per pulse and c_1 and c_2 are constants obtained from the linear fit. This can be applied at any dose per pulse, although the fit constants must be determined at a very low dose per pulse.

The theoretical general collection efficiency, f_{theor} , is described using Boag's relationship:

$$f_{\text{theor}} = \frac{1}{u} \ln(1+u),$$
 (3.11)

We can make use of the same formulation for u as equation (3.7), but with:

$$r_D = \frac{i_{theor}}{VV}, \qquad (3.12)$$

where v is the chamber volume and v is the pulse repetition frequency. For dielectric media with low permittivity, the factor α in equation (3.8) can be approximated by the equation derived by Debye⁵³:

$$\alpha = \frac{e(k_+ + k_-)}{\varepsilon_o \varepsilon}, \qquad (3.13)$$

where ε is the relative permittivity of the medium in the chamber and ε_0 is the permittivity of free space. Using these in equation (3.7) we arrive at:

$$u = \frac{i_{\text{theor}}}{\varepsilon \varepsilon_o E \pi r_{\text{chamber}}^2 \nu}, \qquad (3.14)$$

where r_{chamber} is the radius of the sensitive volume of the chamber.

Again, this theory is applicable only where there is complete charge collection from one pulse before the arrival of the next pulse. It is also limited to field strengths below 1.2×10^6 V/m where higher order terms in Onsager's theory can be considered negligible so that equation (3.10) holds⁵⁴.

3.4 PROPERTIES OF LIQUID ISOOCTANE

For a liquid to be useful in liquid ionization chambers it must have certain key properties. First of all the liquid must be a good insulator, even for high electric fields, in order to keep leakage currents low. It must also have a high ion yield when irradiated in order to produce a sufficient signal for measurements. As well, the density and atomic number should be similar to water and the stopping power ratio water-to-liquid should show very little energy dependence. The mobility of the ions produced in the liquid must be high in order to minimize ion recombination and finally the practicalities of obtaining and handling the liquid must be considered.

2,2,4-trimethylpentane (see Figure 3.2), commonly referred to as isooctane, is the liquid we have used in our studies on liquid ionization chambers for radiation dosimetry. It is an insulating nonpolar hydrocarbon composed of low atomic

number elements. Isooctane has a density of 692 kg/m^3 , which is only 30% less than water, and an effective atomic number of 5.36 which is similar to the effective atomic number of water, 7.42. It should not, therefore, significantly perturb the radiation field when measuring in water or a water-like material.



Figure 3.2 Chemical structure of isooctane (2,2,4-trimethylpentane).

The variation of the mean restricted collision mass stopping power ratio water-toliquid is small over the range of electron energies used clinically, as shown in Figure 3.3. Whereas this ratio changes by 16% for air for electron energies between 1 and 20 MeV, in isooctane the variation is less than 1% over the same energy range.



Figure 3.3 Ratio of restricted collision mass stopping powers versus electron kinetic energy: water/air (solid line) and water/isooctane (dashed line).

The $G_{\rm fi}(0)$ value for isooctane is 0.35 for low LET radiation⁴². As a comparison, the ion yield in air is 2.9 ion pairs per 100 eV. Although this is larger than the $G_{\rm fi}(0)$ value for isooctane, there is far more ionization in isooctane than in air when equal volumes of each are considered. This is because the density of the isooctane is more than 500 times greater than that of air. Another important factor when considering energy dependence is the variation of free ion yield with electron energy. For isooctane, $G_{\rm fi}$ varies by no more than 2% for megavoltage photon and electron beams²⁴. As well, the variation of $G_{\rm fi}$ with temperature is 0.2% to 0.4% per °C (depending on the applied electric field) and there is negligible dependence on the ambient pressure⁵⁵. Isooctane has a relatively high ion mobility for a room temperature liquid. The mobilities of positive and negative ions are both 2.9×10^{-8} m² V⁻¹ s⁻¹ (Ref. 27).

Isooctane is a liquid at room temperature with a boiling point of 98°C. This makes it convenient to handle compared with cryogenic liquid noble gases which

are used often in ionization chambers for high-energy physics due to their high ion mobilities. Even tetramethylsilane (TMS), another insulating liquid often used in ionization chambers, has a boiling point of 26°C, so that, although it has a higher free ion yield and ion mobility, it can be more difficult to handle than isooctane. Isooctane also has a low degree of toxicity (irritating to skin and harmful if swallowed), so it can be handled with minor safety precautions (wearing gloves).

3.5 MOTIVATION FOR THIS WORK

The goal for this project was to develop a liquid-filled ionization chamber that could be used for radiation dosimetry in clinical linear accelerator beams, drawing on our previous experience with liquid ionization chambers. This involved constructing several chamber prototypes and testing their characteristics in terms of stability and reproducibility of response. Once a design was found to be suitable, the recombination characteristics were studied and a method to correct for general recombination in pulsed radiation beams was derived. The energy dependence was evaluated from cross-calibration in two megavoltage photon beams of different energies. Finally, measurements of the build-up region of an 18 MV photon beam were taken and compared with measurements made using other types of detectors. This provided information on the perturbation effects of the chamber as well as the validity of the ion recombination corrections applied. We predicted that a liquid-filled ionization chamber would show less energy dependence and have negligible perturbation effects compared with conventional air-filled ionization chambers.

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Chapter 4

Liquid ionization chambers: Materials and methods

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4.1 THE GLIC CHAMBERS

As explained in the previous chapter, our goal for this work was to construct and characterize a liquid ionization chamber to be used for clinical radiation dosimetry. The first chamber constructed was called the GLIC (Guarded Liquid Ionization Chamber), as its unique feature was the inclusion of a guard electrode. Generally, in liquid ionization chambers, a guard ring does not need to be included since it is not required to prevent in-scatter perturbation effects as it would in air-filled chambers. The purpose behind including it in this design, however, was to allow testing of the chamber both with and without liquid in the sensitive volume. The GLIC was constructed with C552 air-equivalent conductive plastic (Standard Imaging, Middleton) electrodes and Teflon insulators. Due to design and construction issues, this first chamber model was never operational, but experience with this chamber led to improvements in the design of a second model, the GLIC-02.

The GLIC-02, shown in Figure 4.1, also has C552 electrodes and Teflon insulators. The chamber body has outer dimensions of 15 mm diameter and 45 mm length. It is a plane-parallel design and consists of a cap which acts as the outer electrode and is screwed on to the main chamber body. When the cap is screwed on, the separation between the outer and collecting electrodes is 0.7 mm. The collecting electrode is 1.5 mm in diameter and is surrounded by a 0.4 mm thick Teflon insulator followed by a 1.5 mm thick guard ring electrode. The sensitive volume is approximately 2 mm³. A second Teflon insulator surrounds the guard electrode. The base of the chamber is made of C552 as well and the threading provides electrical connection with the outer electrode cap. Two 1 mm outer diameter Teflon tubes were inserted through holes drilled in the chamber body in order to fill the chamber with liquid or to provide venting to the atmosphere when the chamber is used without liquid. Teflon valves were used to allow the ends of the tubes to be closed off. Two Buna-N O-rings were used to seal the liquid in the chamber. In most cases, Teflon and C552 pieces were tightly press-fit into each other, providing a liquid-tight seal without requiring glue. However, in some areas where glue was required, a solvent-resistant epoxy (Master Bond EP41S) was used. The electrodes were connected to a low noise triaxial cable (Huber Suhner G 01330 HT-12) using conductive silver epoxy (ITW Chemtronics CW2400).

Because of issues relating to the short-term stability of the GLIC-02, described in section 4.5, another chamber design was proposed using graphite electrodes rather than C552 plastic. A hypothesis was that the plastic might be introducing impurities into the system, changing the chemical composition, and thereby the radiation response, over time. To initially test whether graphite would be a suitable material, a thin graphite insert was introduced inside the cap of the GLIC-02, covering the region where the liquid was present and acting as the outer electrode. This addition did produce a small improvement in the stability of the response over time, so the decision was made to construct another chamber with graphite electrodes rather than C552.

The GLIC-03 is also shown in Figure 4.1 and the major difference between this chamber and the previous design is that the electrodes of the GLIC-03 are made of graphite (Carbone Lorraine UTR-145). Some additional changes and improvements have also been made to the design of the GLIC-03. The outer cap and chamber body are made from Delrin to make the chamber liquid-tight. The graphite outer electrode was glued into the Delrin cap with solvent-resistant epoxy so that the end face of the cap consists of 1 mm Delrin and 0.5 mm graphite. It was necessary to increase the outer diameter of the chamber to 21 mm to allow for this extra layer. The collecting and guard electrodes have the same diameters as in the GLIC-02, but are made of graphite rather than C552. The length of the chamber body was reduced to 34 mm to allow for easier drilling of the holes for the filling tubes. Rather than Teflon tubing, stainless steel tubes with an outer diameter of 0.8 mm were inserted. The reason for this change was that after a long period of irradiation of the GLIC-02, the Teflon tubes became brittle and developed cracks. Tygon tubing was attached to the outer ends of the stainless steel tubes. Tygon was chosen because it would form a tight seal over the stainless steel. The Tygon tubes are clamped closed after filling the chamber with liquid. The insulators were again made from Teflon. A Buna-N O-ring is used to seal the chamber volume. As with the previous version of the chamber, most pieces were tightly press-fit to make the chamber liquid-tight. Where this was not adequate, solvent-resistant epoxy was used. To prevent wear on the graphite outer electrode when the cap is screwed on and off, a 1 mm thick stainless steel ring was glued to the graphite in the cap with conductive epoxy and the gap between the ring and the Delrin cap was filled with solvent-resistant epoxy.

Electrical connections between the triaxial cable and the collecting and guard electrodes were performed using conductive epoxy. One piece of the chamber body is made of C552 and connected to the outer braid of the triaxial cable with conductive epoxy. It was hoped that this could provide electrical connection with the outer electrode in the cap through surface contact with the stainless steel ring.

This, however, was insufficient, so a 0.8 mm thick brass foil was glued to the top surface of the C552 with conductive epoxy. Following several months of use, the conductive epoxy began to lose contact with the foil. To ensure a better connection, a thin copper wire was run from the outer braid of the triaxial cable through a hole drilled in the Delrin chamber body piece and up to the foil which was glued in place with solvent-resistant epoxy. This provides an excellent connection to the cap when it is screwed on. If a future chamber is designed, the method of connection to the outer electrode should be re-thought, but for the present work, this was found to be a sufficient solution.

The liquid used in all our studies is 2,2,4-trimethylpentane, also called isooctane (Aldrich, anhydrous, 99.8%). This liquid has been used in many liquid ionization chambers for various applications. It has a relatively high mobility, $2.9 \times 10^{-8} \text{ m}^2 \text{s}^{-1} \text{V}^{-1}$ (Ref. 1) and the variation in stopping power ratio isooctane-to-air is very small over the range of energies used clinically. Many studies have also been done with this liquid to determine properties such as temperature dependence² and ion recombination characteristics^{1,3-5}.



Figure 4.1 Schematic diagram showing the cylindrical cross-section of the GLIC-02 and GLIC-03

4.2 MEASURING THE AIR-FILLED GLIC CHAMBER CHARACTERISTICS

Before filling the GLIC chambers with liquid, we examined their properties. For comparison, measurements were also taken with an Exradin A14P chamber, which is similar to the GLIC chambers in terms of design and sensitive volume. Measurements were done for 6 and 18 MV beams from a Varian Clinac 21EX. To determine the absorbed dose to water calibration coefficient at each energy, N_{D_e} , a cross calibration procedure was followed. First of all, measurements were taken with an Exradin A12 chamber (SN 310) which has a ⁶⁰Co absorbed-dose to water calibration coefficient established at the national standards lab, NRC (National Research Council, Ottawa). This chamber was positioned with the center of the chamber at 10 cm water-equivalent depth in a 20×20×20 cm³ Solid Water (Gamex RMI) phantom (Phantom 1 in Figure 4.2). The absorbed dose to water was determined using the procedure of Seuntjens et al.⁶ which describes a

method to derive dose to water for a measurement at an equivalent point in Solid Water. The correction factor $k_{\rm ph}$, which takes into account the difference between water and Solid Water, has a value of 1.000 for 6 MV and 1.006 for 18 MV (Ref. ⁶).Immediately following the measurements with the Exradin A12, measurements were taken with one of the small volume chambers. For the GLIC-02 and Exradin A14P, it was possible to place the chamber in the same Solid Water phantom as was used for the Exradin A12, using a Solid Water sleeve to adjust the point of measurement to the correct position. Because of its larger diameter, another Solid Water phantom (Phantom 2 in Figure 4.2) was needed for the GLIC-03. This phantom consisted of a $30 \times 30 \times 20$ cm³ Solid Water block with a hole of the same diameter as the GLIC-03 drilled in the center. 30×30 cm² slabs of various thicknesses were added in front of the chamber to locate the point of measurement at 10 cm depth. For all measurements, the SSD was 100 cm and the field size was $10 \times 10 \text{ cm}^2$ at the surface of the phantom. Polarity and recombination effects for the air-filled chambers were determined using the method described in TG-51 (Ref. 7). When measuring with the small-volume chambers, the leakage current was measured and corrected for.



Phantom 3

Figure 4.2 Diagram showing the three Solid Water phantoms used in this work. Phantom 1 was used for stability tests and reference dosimetry with the GLIC-02 and for reference dosimetry with the Exradin A12 and Exradin A14P. Phantom 2 was used for reference dosimetry with the GLIC-03 and for PDD measurements with the GLIC-03 and Riga diamond detectors. Phantom 3 was used for stability and ion recombination measurements with the GLIC-03.

4.3 DETERMINING THE ELECTRODE SEPARATION

The sensitive volumes of the GLIC chambers are cylinders with a cross sectional area defined by the size of the collecting electrode and a height defined by the separation between the collecting and outer electrodes. Since the cap of the

chamber is screwed on until it is tight, this electrode separation is not rigorously defined by chamber construction. In order to determine the electrode separation we performed a capacitance test. In this test, the un-filled chamber was connected to a Keithley 6517A electrometer and the polarizing voltage was incremented in steps of 50 V from 0 to 400 V. The charge was measured after each increment. The slope of the linear fit to the charge as a function of voltage represents the capacitance of the chamber. Assuming a perfect parallel plate capacitor, the separation between the plates can be expressed as a function of the capacitance, *C*, and the plate area, *A*, by:

$$d = \frac{\varepsilon_0 A}{C},\tag{4.1}$$

where ε_0 is the permittivity of free space. Because the GLIC-02 and GLIC-03 have large guard rings, we have assumed that the sensitive volume of each chamber behaves as an ideal parallel plate capacitor. The area of the sensitive volume is not easily measured in our case, as the collecting electrode has a small diameter and may not be exactly circular. As well, a small error in the determination of the radius will be magnified by the fact that the radius is squared to determine the area. For this reason we used the calibration factors obtained through cross-calibration to estimate the sensitive volume. Since v = dA, where v is the sensitive volume of the chamber:

$$d = \sqrt{\frac{\varepsilon_0 \mathbf{v}}{C}} \,. \tag{4.2}$$

The cavity dose calibration coefficient is related to the sensitive volume by:

$$N_{D,\text{air}} = \frac{W_{\text{air}}}{e} \frac{1}{\rho_{\text{air}} V}.$$
(4.3)

Where W_{air}/e is the energy required to produce an electron-ion pair in dry air and ρ_{air} is the density of air. $N_{D,air}$ is derived from the measured absorbed dose to water calibration coefficient after correcting for the stopping power ratio water-to-air and neglecting perturbation effects.
4.4 POST-IRRADIATION CURRENT

As mentioned in section 3.2, we performed previous studies using the modified Exradin A14P chamber filled with isooctane (referred to as the Micro-LIC). One of the problems with the use of this chamber was that it exhibited a postirradiation current that decreased over a long period of time before the chamber current returned to its initial value before irradiation. This caused problems because the signal of consecutive irradiations depended on the time between irradiations and it was difficult to determine when to read the collected charge after the beam turned off. We hypothesized that this effect might be due to the empty space between the guard ring and the collecting electrode in this chamber design. It would be possible for liquid to fill this space and for ionization to occur in this liquid volume. However, because both the guard and central electrodes are at the same potential, there is no electric field in this region. Ions could possibly diffuse into the sensitive volume after irradiation stopped and be collected by the collecting electrode once they experienced the electric field in this region. To prevent this in the GLIC-02 and GLIC-03, there is a Teflon insulator between the collecting and guard electrodes. Using a Keithley 6517A electrometer controlled by a PC through the GPIB interface, we read the current at 0.5 s intervals during irradiation and for 120 s following beam off. We examined the post-irradiation response of the GLIC chambers and compared it with the previously measured response of the Micro-LIC.

4.5 STABILITY AND REPRODUCIBILITY OF THE LIQUID-FILLED CHAMBERS

For the GLIC-02, six measurements of the chamber response were taken over a period of 24 hours. The chamber was placed in Solid Water Phantom 1 (Figure 4.2) at 10 cm depth, 100 cm SSD and was irradiated by the 6 and 18 MV beams with a field size of 10×10 cm² at the phantom surface. The 100 MU/min pulse rate setting was used. To monitor the stability of the linear acccelerator output, measurements were also done with the Exradin A12 chamber under the same conditions after each set of measurements with the GLIC-02.

A second stability test was performed in a 60 Co beam. In this case, the GLIC-02 was inserted into a PMMA tube with 5 mm wall thickness that was fixed to a 5 mm thick PMMA accessory tray and the gantry was rotated 180° so that the beam was directed vertically upward. This allowed for a very quick reproducible set-up so that the chamber response could be measured over several days. The stability test on 60 Co was also performed with the graphite outer electrode inserted into the GLIC-02 cap.

The GLIC-03 stability was tested in the 18 MV beam of a Clinac 21EX. The polarizing voltage was set to 500 V and the lowest available dose rate setting (100 MU/min) was used. The chamber was inserted into Solid Water Phantom 3 (see Figure 4.2) which was oriented such that the sensitive volume of the chamber was directed vertically downwards and the phantom was positioned at 100 cm SSD. This phantom also has a hole in which the Exradin A12 chamber could be inserted to monitor changes in beam output. Both chambers were at approximately the same depth of 15 cm in Solid Water.

To determine the necessary pre-irradiation dose to achieve a stable reading, a series of measurements were taken to monitor the response of the chamber. Immediately following a new fill of the chamber liquid, the chamber was given a series of 6 to 10 irradiations of 250 MU. Between each series of irradiations 2500 MU was delivered. For all other measurements, this pre-irradiation dose was delivered initially so that a stable response was achieved. The stability of the chamber response as a function of time following the initial pre-irradiation dose was also assessed under the same irradiation conditions with 100 MU delivered for each measurement. This test was performed on three separate occasions for periods of 5 hours, 7 hours and 24 hours with the Exradin A12 chamber being used to correct for any changes in beam output.

Reproducibility of the chamber response from one liquid fill to another over a period of 8 months was monitored under the same set-up and irradiation conditions described above. Following each fill with new liquid a large preirradiation dose was given and the radiation response to a 250 MU irradiation as well as the leakage current were measured. Again the Exradin A12 chamber was used to correct for any changes in beam output over time.

4.6 ION RECOMBINATION

The method for correcting for ion recombination proposed by Johansson et al.³ There are, however, limitations to the was described in section 3.3.3.2. applicability of this method in our application. First of all, there is an issue with the linearity of the collected charge with increasing electric field, used to determine the constants c_1 and c_2 . More detailed study⁴ has revealed that the collected charge does not continue to increase linearly with increasing electric field. This is due to the fact that as the field increases more terms must be accounted for in the underlying Onsager theory of initial recombination. For isooctane, this departure from linearity occurs at an electric field strength of about 1.25×10^6 V/m. For a chamber with an electrode separation of 0.56 mm, this corresponds to an applied voltage of 700 V. The lower voltage limit on this linear region occurs at approximately 0.75×10^6 V/m, corresponding to 420 V for a 0.56 mm electrode separation. A confounding limitation is the requirement that all charge produced in a pulse be collected before the next pulse occurs. This condition sets a limit on the lowest voltage which can be applied for a given pulse repetition frequency. For a Varian Clinac 21EX, the lowest available pulse repetition frequency is at the 100 MU/min setting. For 18 MV the frequency at this setting is 30 Hz while for 6 MV it is 60 Hz. Again considering a 0.56 mm electrode separation, based on the ion mobility of isooctane, the minimum voltage required is 325 V for 18 MV and 650 V for 6 MV.

Notice that, for the 6 MV beam, we have only a very small range of applicable voltages (650–700 V). This fact makes the evaluation of recombination based on

the method described by Johansson et al. impossible for our chamber in this beam. There is, however, another possible approach. General recombination also varies as a function of dose rate or dose per pulse, while initial recombination is not affected by changes in dose per pulse. If the voltage and pulse repetition frequency are kept constant, an empirical relationship between collected charge and dose per pulse can be determined. Although this approach will not provide an absolute value of the ion recombination, it can be used for relative measurements to correct for different levels of recombination present at different dose rates. This method should be applicable for comparing beams of different pulse frequencies so long as there is complete charge collection from one pulse before the arrival of the next pulse. In a single beam, it can also be applied for various levels of dose per pulse even at a high pulse frequency where there is an overlap of charge from successive pulses.

We performed tests with the GLIC-03 to evaluate the recombination using both of the methods described above. For the method of Johansson et al., we used the 100 MU/min setting with the 18 MV beam and performed measurements with the GLIC-03 and Exradin A12 chambers inserted into Phantom 3 (Figure 4.2). Measurements were performed at different SSDs to achieve different values of dose per pulse which were determined based on the Exradin A12 readings. The applied voltage was varied between 100 and 700 V for all SSDs and the measurements with applied voltages between 500 and 700 V at the farthest SSD were used to determine the constants c_1 and c_2 . Equations (2.10) to (2.14) were then used to determine f_{theor} .

For the second method, the GLIC-03 and Exradin A12 chambers were again inserted in Phantom 3 (Figure 4.2) and the SSD was changed in order to vary the dose per pulse. The variation of response as a function of dose per pulse was used to obtain a relative efficiency. The beams, voltages, dose rate settings and corresponding pulse repetition frequencies tested with this method are listed in Table 4.1.

		Applied voltage (V)	Dose rate setting (MU/min)	Pulse repetition frequency (Hz)
Case I	6 MV	700	100	60
Case II	18 MV	700	100	30
Case III	18 MV	500	100	30
Case IV	18 MV	500	500	180

Table 4.1 Beams, voltages, dose rate settings and corresponding pulse repetition frequencies used in evaluation of recombination for the GLIC-03.

4.7 CROSS-CALIBRATION OF THE LIQUID-FILLED GLIC-03

In order to evaluate the energy dependence of the GLIC-03, the chamber was cross-calibrated in the 6 and 18 MV beams of the Clinac 21EX using the 100 MU/min dose rate setting. The absorbed dose to water in Solid Water was measured using the Exradin A12 chamber in the same manner as described in section 4.2. The response of the GLIC-03 was measured for the same irradiation conditions $(10 \times 10 \text{ cm}^2 \text{ field}, 100 \text{ cm} \text{ SSD}, 10 \text{ cm} \text{ depth})$ in the Solid Water Phantom 2 (Figure 4.2). The voltage applied to the chamber was 700 V and the response was measured at both positive and negative polarities. Corrections for relative differences in ion recombination between 6 and 18 MV were made using the curves of response as a function of dose per pulse for this voltage and these beams.

4.8 PDD MEASUREMENTS IN SOLID WATER

The PDD in Solid Water was measured for an 18 MV beam in the build-up region using 3 different detectors: the air-filled GLIC, the liquid-filled GLIC and a Riga diamond detector. All measurements were performed in Solid Water Phantom 2 (Figure 4.2). Detectors were positioned so that their front face was flush with the surface of the $30 \times 30 \times 20$ cm³ block and then various thicknesses were added in

front of the detector to vary the depth. The phantom was placed on a translatable stage and was moved as each thickness was added so that the phantom surface remained at 100 cm SSD. The precision of the positioning is estimated to be ± 0.2 mm. The Solid Water slabs used in front of the detectors had certification documents which listed their thicknesses to the nearest 0.01 mm. The dose rate setting was 500 MU/min and the field size was 10×10 cm². Measurements were taken at both + and -300 V with the air-filled GLIC-03 and the average was taken to correct for polarity effects. For the liquid-filled GLIC-03, the voltage applied was 500 V and relative corrections for recombination as a function of dose rate were determined from the 500 V, 500 MU/min, 18 MV curve. For the diamond detector, a polarizing voltage of +100 V was applied.

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Chapter 5

Liquid ionization chambers: Results and discussion

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The results presented in this chapter have been published in the journal Physics in Medicine and Biology¹. Permissions to reproduce the material are included at the end of this thesis.

5.1 AIR-FILLED PROPERTIES OF THE GLIC-02 AND GLIC-03

The air-filled characteristics of the two GLIC chambers are listed in Table 5.1. As well, characteristics of a commercial chamber of similar dimensions, the Exradin A14P, are listed for comparison. Reproducibility on these values was within 0.25%. The leakage current was always less than 0.3% of the measured signal for the GLIC-02 and Exradin A14P chambers. For the GLIC-03, the leakage signal was larger, but stable and less than 4% of the measured signal.

	GLIC-02	GLIC-03	Exradin A14P
sensitive volume thickness (mm)	0.70	0.56	1.0
<i>p</i> _{ion} 18 MV	1.000	1.000	1.007
6 MV	1.000	1.000	1.008
$p_{\rm pol}$ 18 MV	0.997	0.993	1.170
6 MV	0.987	0.981	1.190
N_{D_w} (cGy/nC) 18 MV	974.4	1377	889.2
6 MV	1003	1406	907.5
ratio of $(N_{D_w} 18MV)/(N_{D_w} 6MV)$	0.9715	0.9792	0.9798

 Table 5.1 Properties of the air-filled GLIC-02, GLIC-03 and Exradin A14P

 chambers

5.2 ELECTRODE SEPARATION

After determining the capacitance by the method described in section 4.3, we used the volume determined from the cross-calibration to find the plate separation according to equation (4.2). The electrode separations of the GLIC-02 and GLIC-03 are 0.70 and 0.56 mm respectively. These values are relatively insensitive to uncertainties in the volume determination. A 10% error in the volume results in an error in the separation of only 0.03 mm. In contrast, if the physical radius is used to determine the thickness, then a 0.1 mm error in the radius will result in an error in electrode separation of 0.15 mm. For the GLIC-03, based on the volume determined using the calibration factor and the capacitance measurements, the sensitive volume has a radius of 1.1 ± 0.05 mm. This is much larger than the physical radius of 0.75 mm. The large difference between these two values may be related to alterations in the electric field due to the insulator between the collecting and guard electrodes.

5.3 POST-IRRADIATION CURRENT

Figure 5.1 shows the post-irradiation current for the GLIC-02, GLIC-03 and Micro-LIC. When normalized to the current 10 s after the end of an irradiation, the Micro-LIC current drops by an additional 71% over the 120 s after beam off, while the GLIC-02 current drops by 47% and the GLIC-03 by only 20%. This remaining residual current could be the result of charge accumulation on the insulator between the collecting and guard electrodes. During measurements with the GLIC-03 chamber, we applied a measurement protocol where the electrometer reading was taken 60 s after the irradiation finished and then we waited another 60 s before beginning the next irradiation or leakage current measurement. By this method we hoped to avoid any inconsistencies due to the variations in current following irradiation.



Figure 5.1 Post-irradiation current for GLIC-03 (dashed line), GLIC-02 (solid line) and Micro-LIC (dotted line) normalized to the current 10 s after beam off.

5.4 STABILITY AND REPRODUCIBILITY

Figure 5.2 shows the stability of the GLIC-02 measured in the 6 and 18 MV beams. There was considerable change in the response over 24 hours. Also, the response initially decreased and then increased, thus making a correction for response change difficult to predict.



Figure 5.2 Uncorrected response of the GLIC-02 as a function of time for 6 MV (open circles) and 18 MV (filled triangles) beams from the Clinac 21EX.

The results of the stability tests with the GLIC-02 in a ⁶⁰Co beam are shown in Figure 5.3. In this case, the response was measured over several days. For the first day the GLIC-02 showed unpredictable variations of up to 4%. When the graphite electrode insert was added, the behavior on day one improved substantially, with less than a 1.5% change over four hours and a consistent increasing trend following the first hour. However, on subsequent days the chamber behavior became increasingly erratic and showed a large variation in both cases. Still there was some indication that graphite improved the chamber stability which is why the GLIC-03 was constructed with graphite electrodes.



Figure 5.3 Arbitrarily normalized response of the GLIC-02 in a 60 Co beam. (a) and (b) are the response as a function of time for the first day after filling the chamber for the GLIC-02 and the GLIC-02 with the graphite electrode insert respectively. (c) shows the response of the GLIC-02 from (a) for day 1 and continued measurements over the following three days as a function of cumulative irradiation time in the 60 Co beam. (d) shows the response of the GLIC-02 with the graphite electrode insert from (b) for day 1 and continued measurements over the following six days as a function of cumulative irradiation time in the 60 Co beam.

With the GLIC-03, we were able to achieve a stable response following a large pre-irradiation dose. Figure 5.4 shows that, although changes in chamber response of over 30% could be observed initially over the delivery of the first 14500 MU (sets a-c), the measurements that followed (sets d and e) had a variation of less than 5% while an additional 5750 MU was delivered and the final 9 measurements (set e) have a variation of less than 1%.



Figure 5.4 Relative response of the GLIC-03 over the initial 41 measurements after a new liquid fill. The five different sections (a-e) represent series of readings for an irradiation of 250 MU. Before each series 2000 MU was delivered.

When monitoring the response over time following a pre-irradiation dose, it can be seen from Figure 5.5 that, although there is a decrease in response of more than 2% over 24 hours, this decrease is stable and reproducible, so it would be possible to correct the readings accordingly. Additionally, the change is only 1% over 10 hours, so the correction would be insignificant for measurements over a short time interval.



Figure 5.5 Response of the GLIC-03 for three different liquid fills tested over periods of 5, 7 and 24 hours following pre-irradiation. Each point represents the average of 8 readings for an irradiation of 100 MU with error bars indicating one standard deviation. The straight line is a linear fit to all of the data points.

When examining the reproducibility of the chamber response each time the chamber is filled with new liquid, Figure 5.6 indicates that this is never more than 5% different from the mean. The leakage current is also consistently less than 1% of the signal measured with a dose rate of approximately 63 cGy/min. The collection of data examining the stability as a function of fill provides a good indication of whether or not drastic changes in chamber or liquid properties have occurred, for example impurities in the liquid.



Figure 5.6 Relative response of the GLIC-03 after each new liquid fill. Filled symbols indicate the relative response and correspond to the values on the left axis. The dose rate was approximately 63 cGy/min and each point represents the average of 5 measurements with one standard deviation indicated by the error bars. Open symbols indicate the leakage current expressed as a percentage of the chamber response and corresponding to the values on the right axis.

5.5 ION RECOMBINATION

Figure 5.7 shows the theoretical general collection efficiency, f_{theor} , as a function of electric field strength for the GLIC-03 calculated according to equations (2.10) to (2.14) for different values of dose per pulse. For the lowest dose per pulse (0.05 mGy/pulse), f_{theor} is greater than 0.997 at all field strengths. Note that for the highest dose per pulse value shown here (0.36 mGy/pulse), the collection efficiency is lower than 0.986 even at the highest field strength, corresponding to 700 V. This decrease in collection efficiency is important as many typical clinical measurements are done with a dose per pulse as high as 0.6 mGy/pulse, where f_{theor} would be reduced to below 0.978 according to this method of calculation.



Figure 5.7 Theoretical general collection efficiency of the GLIC-03 calculated according to equations (2.10) to (2.14) as a function of electric field strength. The range of electric field strengths corresponds to a range of polarizing voltages between 450 V (0.80×10^6 V/m) and 700 V (1.25×10^6 V/m). Values are shown for different dose per pulse rates: (from top to bottom) 0.05 mGy/pulse, 0.07 mGy/pulse, 0.10 mGy/pulse, 0.18 mGy/pulse and 0.36 mGy/pulse.

As was mentioned in section 4.6, there are cases where the method of Johansson et al. is not applicable to measurements with the GLIC-03. In particular, measurements in the 6 MV beam or other measurements where we would like to use a higher pulse repetition frequency. In order to correct for ion recombination in these cases, we used the second method described in section 4.6, where the relative efficiency is determined as a function of dose per pulse and normalized at an arbitrary value of dose per pulse. The lines in Figure 5.8 show this relative efficiency for the 4 cases listed in Table 3.1, normalized to unity at a dose per pulse of 0.1 mGy/pulse. This is a linear fit to the data measured when varying the

For Case II (18 MV, 700 V, 100 Mu/min), f_{theor} agrees with the measured relative efficiency within 0.2%, however, the difference is larger (up to 0.6%) for Case III (18 MV, 500 V, 100 MU/min). Because there is incomplete charge collection from one pulse before the next pulse occurs, the efficiency as a function of dose per pulse is much lower for Case IV (18 MV, 500 V, 500 MU/min), and the theoretical efficiency calculation cannot be applied. In the case of the 6 MV beam (Case I), since the pulse frequency is double that at 18 MV, it was not possible to apply a large enough range of electric field strengths to use the method of Johansson et al. to determine c_1 and c_2 , so here again values of f_{theor} could not be calculated.



Figure 5.8 Relative efficiency for the GLIC-03 as a function of dose per pulse. Lines indicate the relative efficiency based on a linear fit to measurements done with different dose per pulse values for the conditions given in Table 3.1: Case I - 6 MV, 700 V, 100 MU/min (solid line), Case II - 18 MV, 700 V, 100 MU/min (dashed line), Case III - 18 MV, 500 V, 100 MU/min (dotted line) and Case IV - 18 MV, 500 V, 500 MU/min (dot-dashed line). Symbols indicate the efficiency calculated using equations (2.10) to (2.14)and normalized to 1 at a dose rate of 0.1 mGy/pulse for Case II - 18 MV, 700 V, 100 MU/min (open symbols) and Case III - 18 MV, 500 V, 100 MU/min (filled symbols).

5.6 ENERGY DEPENDENCE

For the 6 and 18 MV beams with 700 V and 100 MU/min, the relative efficiencies agree within 0.3%, indicating that there is not a substantial difference between the recombination behavior for these two beams, although they have very different pulse frequencies. We therefore considered it valid to apply corrections for the relative efficiency of each beam based on the linear fits shown in Figure 5.8.

Using the p_{ion} corrections and the data obtained from cross-calibration against the Exradin A12 chamber, the ratio of the absorbed dose calibration factors $(N_{D_w} 18 \text{ MV})/(N_{D_w} 6 \text{ MV})$ is 0.989±0.004. This is 1% closer to unity than the same ratio calculated for the air-filled GLIC-03 of 0.979±0.003, indicating that there is less energy dependence for the liquid-filled GLIC-03.

5.7 PDD MEASUREMENTS IN THE BUILD-UP REGION

The results of the PDD measurements taken with the liquid-filled GLIC-03, airfilled GLIC-03 and Riga diamond detector are shown in Figure 5.9. The readings of the liquid-filled GLIC-03 were corrected for relative differences in recombination using the 18 MV, 500 V, 500 MU/min linear fit (Case IV) from Figure 5.8. Note that the range of dose rates is from 0.25 to 0.56 mGy/pulse, so the relative difference in p_{ion} corrections used is 3.7%. Figure 5.10 shows the percent difference between the PDD measured with the liquid-filled GLIC-03 and both the air-filled GLIC-03 and diamond detector measurements from this study. As well, the liquid-filled GLIC-03 is compared with PDD measurements in Solid Water from Abdel-Rahman et al.². These measurements were taken with the IC-10 cylindrical chamber, the PTW Roos plane-parallel chamber and the PEEC extrapolation chamber. All measurements have been scaled to an equivalent depth in water.



Figure 5.9 PDD curves measured in Solid Water with the liquid-filled GLIC-03 (solid line), air-filled GLIC-03 (dashed line) and Riga diamond detector (dotted line) as a function of the water-equivalent depth.



Figure 5.10 Percent difference between the PDD measured with the liquid-filled GLIC-03 and other detectors: IC-10 (thin solid line) (Ref. 2), Riga diamond detector (dashed line), PTW Roos chamber (dotted line) (Ref. 2), PEEC extrapolation chamber (dot-dash line) (Ref. 2), and air-filled GLIC-03 (thick solid line).

The liquid- and air-filled GLIC-03 measurements agree within 0.5% over the entire measured PDD. Compared with the diamond detector, the liquid-filled GLIC-03 is more than 5% lower for measurements near the surface, but agrees within 1% beyond 16 mm depth. In comparison to the measurements from Abdel-Rahman et al.², the largest difference between the liquid-filled GLIC-03 and the PEEC extrapolation chamber is 1.4% and beyond a depth of 6 mm, the agreement is better than 0.7%. Similarly for the PTW Roos chamber, the largest difference is 2.5% near the surface and agreement is better than 0.5% beyond 4 mm depth. The situation is different for the IC-10 chamber, which has a

response more than 20% higher than the liquid-filled GLIC-03 at 2.5 mm depth. This difference reduces to less than 1% beyond 22 mm depth.

The good agreement between both the liquid- and air-filled GLIC-03 measurements and those taken with the PEEC extrapolation chamber indicates that the GLIC-03 chamber has a very small perturbation effect whether or not it is filled with liquid. Since the chamber volume is so tiny and the guard ring is large compared to the radius of the collecting electrode, this is to be expected. The IC-10 chamber, on the other hand, causes significant perturbation to the radiation field and therefore shows a large over-response at shallow depths. The response of diamond detectors has been shown to depend on the dose rate³. Based on the results for the PTW 60003 diamond detector reported by Laub et al. (Ref.³), we would expect a 3% over-response of the diamond detector at the shallowest depth measured compared with the response at d_{max} . The difference we observed is almost 6%, but more study of the dose rate response of our particular detector would be necessary to determine the appropriate correction for dose rate in our case. The fact that the liquid- and air-filled GLIC-03 measurements agree within 0.5% indicates that our method of correcting the liquid-filled chamber response for general recombination effects is appropriate even though the relative corrections for general recombination are large (up to 3.7%).

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Chapter 6

Liquid ionization chambers: Conclusions and future work

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6.1 CONCLUSIONS

The purpose of this work was to construct and test the properties of a liquid ionization chamber. Two re-fillable detectors with guard electrodes were constructed, the GLIC-02 and GLIC-03. Using a well-guarded chamber is advantageous as the properties can be tested first without filling the chamber with liquid. The air-filled characteristics of both chambers are equivalent or superior to a similar commercial air-filled chamber, the Exradin A14P. When filled with liquid, the GLIC-03 showed superior behaviour to the GLIC-02 in terms of stability and reproducibility, due to the use of graphite rather than C552 electrodes. Impurities in the liquid can affect the chamber response, stability and leakage current. Monitoring the chamber response and leakage current each time it is filled with liquid provided a way to detect changes in liquid purity or chamber behaviour. The response of the GLIC-03 decreased by 1% over 10 hours, however, this decrease in response was stable, linear and reproducible.

One of the significant issues related to measurements with liquid ionization chambers is the correction for ion recombination, since this is much larger in liquids than it is in gases. We first used the method described by Johansson et al.¹ which modifies Boag's theory of general recombination in gases²⁻⁴ and applies it to liquids. Because this theory has limitations related to the maximum pulse repetition frequency and the non-linear behaviour of Onsager's theory of initial recombination at high electric field strengths^{5,6}, we proposed a second method for general recombination corrections in cases where the method of Johansson et al. was not applicable. This second method relates the general collection efficiency to the dose per pulse and was used to derive relative corrections for general recombination. The two methods agreed within 0.2% for the 18 MV, 700 V, 100 Mu/min case and within 0.6% for the 18 MV, 500 V, 100 Mu/min case.

One advantage expected with liquid ionization chambers is a lower energy dependence, since the ratio of the mean restricted collision mass stopping power water-to-isooctane varies by less than 1% over a range of electron energies between 1 and 20 MeV, while, over the same energy range, the stopping power ratio water-to-air varies by 16%. We found that the liquid-filled GLIC-03 had an energy dependence of $1.1\pm0.4\%$ while the air-filled GLIC-03 had a $2.1\pm0.3\%$ energy dependence, when comparing the response between the 6 and 18 MV beams from a Clinac 21EX.

We also compared PDD measurements of the build-up region of the 18 MV beam from a Clinac 21EX. This served two purposes. First of all, since we used a high pulse repetition frequency, where the method of Johansson et al.¹ was not applicable, we were able to test whether our method of correcting for relative differences in general recombination based on response as a function of dose per pulse was valid. The measurements were taken with values of dose per pulse ranging from 0.25 to 0.56 mGy/pulse, and the general recombination correction varied by 3.7% over this range of dose per pulse. The second purpose of these measurements was to examine the amount of perturbation caused by the liquid-

filled or air-filled GLIC-03. We compared our measurements to measurements taken with the PEEC extrapolation chamber⁷, which should produce negligible perturbation as well as the IC-10 chamber⁷, which is known to have a large perturbation effect at depths near the surface.

The excellent agreement between the liquid- and air-filled GLIC-03 measurements and the measurements with the PEEC extrapolation chamber indicates that, whether this chamber is filled with air or liquid, it produces negligible perturbation. As well, this agreement provides confirmation of the validity of correcting for relative differences in general recombination as a function of dose per pulse. This method could then be used for other relative measurements in cases where the method of Johansson et al.¹ is not applicable.

6.2 RECOMMENDATIONS FOR FUTURE WORK

6.2.1 Improvements to the chamber design

In order to continue work with liquid ionization chambers it would be beneficial to consider new chamber designs. The following are a few recommendations for new designs based on experience with the current chambers.

- 1. In order to produce a chamber with good long-term stability, it is important to carefully consider the most appropriate materials. Ideally, these materials would allow for achieving and maintaining a high-purity system. It may also be beneficial to consider using liquids that have undergone additional purification. Ultimately, it would be best to have a completely sealed high-purity liquid volume that could be maintained. One would hope that with sufficient irradiation of such a system, a steady-state could be achieved so that the response would no longer change with time or radiation dose.
- 2. A new design should have a more precisely defined sensitive volume thickness that will remain constant. The screw-on outer electrode made

defining and maintaining a constant electrode separation difficult to achieve. This separation distance is particularly important in assessing recombination as it is a factor in determining the electric field strength and the ion transit time.

3. Improve the electrical connection for the outer electrode. In the present design of the GLIC-03, there were problems with maintaining adequate electrical connection for the outer electrode due to the fact that it was located in a cap that screwed on to the chamber body. This meant that it relied on only physical contact to provide a connection to the outer braid of the cable. An alternative design with a more reliable connection should be considered.

Whether any of these changes will be useful for a new design would depend on what the aim of the study is. Many additional changes might also need to be considered for specific applications.

6.2.2 Further areas to investigate with liquid ionization chambers

There remain many more areas that can be studied both in terms of the properties and characteristics of liquid-filled ionization chambers as well as their application to clinical radiation dosimetry. Further investigation of methods to correct for ion recombination is necessary, particularly in beams with high pulse repetition frequency, such as the electron beams from most clinical linear accelerators. Energy dependence should be examined over a wider range of electron energies. Investigations using other non-polar liquids would also be of interest. Finally, issues related to long-term stability of liquid ionization chambers should be considered.

There are several areas where liquid ionization chambers could potentially be useful in clinical radiation dosimetry. These include IMRT, where, because of the many small overlapping fields, there are concerns with energy dependence, fluence perturbation and detector size for detectors used in IMRT dosimetry. For dosimetry of small radiation fields such as those used for radiosurgery, a small, energyindependent detector with negligible perturbation would also be very useful. There may be further applications in dosimetry for low-energy brachytherapy sources, where high spatial resolution is important but the dose rate is often too low to produce sufficient signal in small air-filled ionization chambers and the dose varies greatly with depth.

With further understanding of the behavior of liquid ionization chambers and continued efforts in improving designs of these detectors, liquid ionization chambers could become a useful tool for clinical medical physicists by providing more accurate radiation dose measurements. This would improve the overall accuracy of radiation delivery to patients undergoing radiation therapy and potentially could improve the outcome for these patients.

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Chapter 7

Introduction to water calorimetry and dosimetry standards

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7.1 INTRODUCTION TO WATER CALORIMETRY

Absorbed dose to water, D_w , can be determined from a very simple relationship

$$D_{\rm w} = c_{\rm w} \Delta T_{\rm w} \prod_i k_i , \qquad (7.1)$$

where c_w is the specific heat capacity of water at constant pressure, ΔT_w is the change in water temperature and k_i are various correction factors (these corrections will be discussed in the following sections). Several significant reviews on the use of water calorimetry for radiation dosimetry have been written¹⁻³. Many of the earliest studies used small thermally isolated cells of water. For example, Busulini

et al.⁴ used a small volume (6 ml) cell to irradiate water and ferrous sulphate (Fricke) solution and used the measured temperature change of water to determine the radiation chemical yield (G-value) for the Fricke solution. Peterson performed a similar calorimetric study to evaluate G-values for Fricke solution for both highenergy electron and ⁶⁰Co beams⁵. In this work the change in temperature was measured by monitoring the volume expansion of irradiated water in a thermally isolated container. A flow calorimetric method was also used to determine electron beam energy, using the temperature difference between water flowing into and out of the calorimeter in which an electron beam was totally absorbed⁶. In these early studies the temperature rise of the entire volume was used to determine the average absorbed dose in the volume, however, none of these studies used water calorimetry to determine the absorbed dose to water at a point.

It would seem that water would be the ideal medium for establishing the quantity of absorbed dose to water, however, for many years there was considered to be an unavoidable technical difficulty that ruled out the use of water calorimetry for determining absorbed dose at a point. In solid-body calorimeters it is possible to construct a thermally isolated segment so that there is no significant heat transferred from this element during irradiation and the absorbed dose is measured in a small volume. If the same method is applied to water, any wall that would isolate a small enough mass of water, on the order of 1 g, would significantly perturb the measurement.

Domen was the first to provide a new perspective to this problem⁷. He showed that, because of the thermal properties of water, thermal isolation was not necessary and dose could be measured at a point in a large volume of water. When considering conductive heat transport, the important property is the thermal diffusivity, α . The value of α for graphite is 8.0×10^{-5} m² s⁻¹, while for water $\alpha = 1.4 \times 10^{-7}$ m² s⁻¹, over 500 times smaller. Since the time that a temperature profile will remain stable is inversely proportional to α , the time available to take a calorimeter measurement is

about 500 times longer for water than for graphite without thermal isolation. For example, for typical irradiation conditions in a 60 Co beam, in order to measure the absorbed dose in a continuous medium with an uncertainty less than 0.5% the measurement time must be less than 2.5 s and 1400 s for graphite and water respectively.

7.1.1 Large unsealed water calorimeters

Domen's original water calorimeter⁸ consisted of a $30 \times 30 \times 30$ cm³ volume of oncedistilled water. In this water volume two thermistors were inserted, sandwiched between thin polyethylene films. The calorimeter was designed to be irradiated from the top by a ⁶⁰Co beam. The water phantom was thermally isolated, but remained open to the atmosphere. Several other calorimeters were made following this same general design and these were used for dosimetry of high energy photon and electron beams^{9,10}, medium-energy x-rays² and neutrons^{11,12}.

The results of these studies indicated complications with using this type of system for absolute dosimetry. Most of the high-energy photon and electron beam measurements with these water calorimeters gave an absorbed dose between 2 and 4% greater than the dose determined using ionization chambers while for neutron beams the results were a few percent smaller and for low energy x-ray beams the results were up to 7% higher².

7.1.2 The chemical heat defect for water systems

The most likely mechanism for this difference was considered to be the chemical heat defect of the water (although later studies raised the possibility of convection effects due to the thermistor power, as will be discussed in section 7.1.4.1). The radiolysis of water produces many species (H^+ , OH, e_{aq} , H_2O_2 , H, OH⁻, H_2 , HO₂). These radiolysis products are unstable and undergo many chemical reactions to ultimately form stable products. These chemical reactions are endothermic or exothermic, so the overall energy balance for an irradiated system may be either positive or negative compared with the expected temperature rise from the absorbed

radiation dose alone. The heat gained or lost due to these chemical reactions is called the chemical heat defect. Because the concentrations of the radiolysis products depend on the LET of the incident radiation, the heat defect will be different, for example, when measuring in high-energy photon beams than in neutron beams.

Boyd et al. compiled a list of the reactions and yields for low LET radiation to examine the product concentrations as a function of time¹³. This model became the basis for further studies done to calculate the heat defect for water saturated with different gases or gas mixtures (air, hydrogen, oxygen, nitrogen...) for low LET radiation^{14,15} as well as neutrons¹⁶ and low-energy x-rays¹⁷. The calculations for air-saturated water indicated that the expected measurement would be 2% lower due to endothermic chemical reactions¹⁵. This was significantly different from the reported 2 to 4% high results with the large open water calorimeters. However, small concentrations of impurities can lead to large and unpredictable differences from the calculated heat defect. Since the water in these calorimeters was in contact with various materials such as plastics and was exposed to the atmosphere, impurities could have been introduced into the water.

Extensive studies were carried out by Klassen and Ross¹⁴ to measure relative differences in the heat defect in a wide range of aqueous systems. These measurements were carried out in a small sealed glass calorimeter vessel so that the water purity and the gas saturation could be carefully controlled. They found good agreement between measured and calculated values of the chemical heat defect, particularly for systems which contained a scavenger for the OH radical (H₂O₂, H₂, CO, formate). Systems where the OH radical was not scavenged (Ar, N₂, O₂, N₂O) appeared to be more sensitive to impurities.

7.1.3 Sealed water calorimeters

The studies of Klassen and Ross indicated that if the water purity and dissolved gases are controlled, the heat defect of a water system can be accurately calculated.

Therefore second-generation calorimeters were built with sealed volumes in which the water quality could be well-controlled. In one of the first examples, built at Yale¹⁸, the entire water volume was sealed in glass. The results using this calorimeter for high-energy photon beam measurements agreed within 0.4% with ionization chamber results¹⁹. Domen came up with an alternative design²⁰ where a small, cylindrical glass vessel containing high-purity water was placed in a large water phantom. The results with this calorimeter for N₂ and H₂ saturated water systems agreed within 0.5% with graphite calorimetry results, a much better agreement than the 3.5% difference reported for the large, unsealed calorimeter. Seuntjens et al.¹⁷ constructed a calorimeter for measuring absorbed dose for medium-energy x-rays (100-250 kV) with a similar design to that of Domen, but using PMMA rather than glass as the vessel material. Although the response of this system appeared to be sensitive to impurities that entered the water from the PMMA walls, the results did confirm the differences in response for water solutions with controlled amounts of different impurities.

7.1.4 Heat transport effects

There are three mechanisms by which heat may be transported: conduction, convection and radiation. In water calorimetry, radiative heat transport is negligible, however conductive and convective heat transfer may be significant, affecting the measured temperature increase.

7.1.4.1 Convection effects

Besides the heat defect, a major concern with using water for absorbed-dose calorimetry, as opposed to solids such as graphite, is the possibility of convective motion in the water. In calorimeters irradiated from above, such as the first-generation unsealed Domen calorimeter, it was assumed that convective heat transport could be ignored when measuring at depths beyond the depth of maximum dose⁸. In this case the temperature of the water when irradiated decreases with increasing depth, so the liquid should remain stable. However, convection currents were reported for horizontally directed beams²¹. Domen proposed using physical convective barriers to prevent this effect from significantly

affecting the results²². In the second-generation sealed water calorimeter, the vessel was assumed to act as a convective barrier²⁰.

The above arguments do not take into account the effect of other materials in the water on the thermal gradients. Materials with specific heat capacities significantly lower than water, such as glass, will heat up more than the surrounding water, producing a larger temperature gradient. There is a further problem in the region around the thermistor probes. Due to power dissipation in the thermistors, there is a very steep temperature gradient surrounding them. Domen did some initial analysis on convection produced by thermistor heating in open calorimeters^{22,23} which suggested that convection can be greatly reduced if the thermistors are operated at a low power of a few μ W and convective barriers are introduced. Seuntjens et al. performed extensive numerical heat transfer calculations in which convective motion was modeled in detail for sealed water calorimeters²⁴. The results of this study indicated that both thermistor power dissipation and dose profile nonuniformity were significant sources of convective motion in calorimeters operated at room temperature. This convective motion was present both outside and inside the sealed calorimeter vessel and the convective velocities depended on the vessel diameter relative to the field size as well as the thermistor power. Convection could produce errors of 1% and 3% for photon and electron beams respectively³, depending on the thermistor power, vessel size and irradiation conditions. These findings were not supported, however, by the experimental study of Domen and Domen²⁵ with the NIST sealed water calorimeter. This study found no evidence of convective motion within the calorimeter vessel, and, although convection was present outside the vessel, the effect on the measured temperature change was determined to be on the order of 0.1%.

One way to deal with these potentially large and difficult to predict convective effects is to operate in conditions where convection is negligible. The density of water at room temperature decreases by about 0.02% per degree of temperature rise, however, at 3.98°C the expansion coefficient of water passes through zero (water
reaches a maximum density). There is then no buoyant force to drive convection. If the water temperature remains within 0.1° of 4° C, the expansion coefficient is less than 1% of its value at room temperature. This method was first used by Schultz et al.²¹ and most current water calorimeters operate at 4°C to avoid convection effects. The exception is the NIST sealed water calorimeter, which is operated at 22°C. Fortuitously the design of the vessel in this calorimeter is such that convection effects are small²⁵.

7.1.4.2 Conductive heat transfer effects

Even if convective heat transfer is eliminated, there remains heat transfer due to conduction. As discussed in the previous section, excess heat is produced by two major sources in water calorimetry: non-water materials (e.g., glass) with a lower heat capacity and different radiation absorption than water and electrical power dissipation in thermistors. The non-uniformity of the dose distribution in the water and resulting thermal gradients may also produce heat gain or loss. The difference in temperature at the measurement point due to conduction can be calculated as a function of time using the conductive heat transport equation:

$$\rho c \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = \rho \dot{D}, \qquad (7.2)$$

where ρ and *c* are the density and specific heat capacity of the medium, respectively, *t* is the time, *k* is the thermal conductivity, *T* is the temperature and \dot{D} is the absorbed dose rate.

Numerical techniques such as finite element analysis have been used to solve the heat transport equation in order to simulate the effect of thermal gradients on the measured temperature²⁶⁻²⁸ and these calculated effects have been verified by measurements^{26,29}. The magnitude of the correction for this effect depends on the irradiation time, dimensions and geometry of the glass vessel and thermistor probes and the dose profile non-uniformity. The effects of conductive heat transport are minimal when using large diameter vessels (where the thermistor probe is far from the glass walls) in radiation beams with a shallow dose gradient (e.g., high-energy

photon beams). For small vessels and beams with steep gradients, such as low energy electron beams, the effects of thermal conduction are much more significant.

7.1.5 Applications of water calorimeters to radiation dosimetry

The primary application of water calorimetry to radiation dosimetry currently is in establishing the standard of absorbed dose to water for ⁶⁰Co (Ref. 28,30,31) as will be discussed in section 7.3. This application has been extended now to include absorbed dose standards for high-energy photon beams^{32,33}. There has also been significant work done with using water calorimetry to measure the absorbed dose beam quality conversion factors for ionization chambers in high-energy photon beams³⁴⁻³⁷. These factors are used in clinical dosimetry protocols and will be discussed further in section 7.4. Water calorimetry has also been used for measurements in medium-energy x-ray beams¹⁷ and proton beams³⁸⁻⁴¹ and there are investigations being done on applying water calorimetry to scanned proton beams⁴². First-generation calorimeters were used to study neutron beams^{11,12} and high energy electron beams¹⁰ as well. While most water calorimeters are operated in standards laboratories, the Nederlands Meetinstituut (NMi) has developed a transportable calorimeter⁴³ that has been used for measurements in photon beams from clinical linear accelerators.

7.2 STANDARDS OF ABSORBED DOSE TO WATER

As mentioned in section 1.2, the quantity of interest in clinical dosimetry is absorbed dose to water. In order to provide a basis for the determination of absorbed dose, primary standards are maintained both nationally and internationally. Current standards use one of three detector types for determination of absorbed dose:

- 1. ionization chambers
- 2. ferrous sulphate solution
- 3. calorimeters

The method of determining absorbed dose from measurements with any of these systems can be expressed in the following general form⁴⁴:

$$D_{w} = mCR_{m}^{w}\prod_{i}k_{i}, \qquad (7.3)$$

where D_w is the absorbed dose to water, *m* is the detector measurement, *C* is the absorbed dose conversion coefficient to convert the measured quantity into absorbed dose in the detector medium, R_m^w is the ratio of dose to water divided by dose to the detector medium and k_i are correction factors.

7.2.1 Ionization chamber-based absorbed-dose standards

The determination of absorbed dose from ionization chamber measurements is described by Boutillon and Perroche⁴⁵. Ionization chambers used for determination of absorbed dose are thick-walled graphite chambers specially designed so that the sensitive volume of the gas is well known. If such a chamber is placed in a water phantom and measurements are taken in a photon beam, then absorbed dose to water is determined according to the following equation:

$$D_{\rm w} = \frac{Q_{\rm air}}{\underbrace{\rho_{\rm air} V}_{m}} \underbrace{\frac{W_{\rm air}}{e}}_{C} \underbrace{\overline{s}_{\rm gr,air} \left(\overline{\mu}_{\rm en}/\rho\right)_{\rm w,gr} \Psi_{\rm w,gr} \beta_{\rm w,gr}}_{R_{\rm air}^{\rm w}} k_{\rm cav} k_{\rm m} k_{\rm h} k_{\rm ion} k_{\rm other}, \qquad (7.4)$$

where Q_{air} is the charge measured in the air volume, ρ_{air} is the air density, v is the sensitive volume, W_{air} is the energy required for an electron to produce an ion pair in air, $\overline{s}_{gr,air}$ is the ratio of restricted mass collision stopping powers graphite/air, $(\overline{\mu}_{en}/\rho)_{w,gr}$ is the ratio of mass energy absorption coefficients water/graphite, $\Psi_{w,gr}$ is the ratio of photon energy fluences at the points of interest in water and graphite and $\beta_{w,gr}$ is the quotient of the ratios of absorbed dose to collision kerma in water and graphite. k_{cav} accounts for the departure from ideal Bragg-Gray cavity conditions since the cavity has a finite size and therefore introduces a perturbation of the radiation field. k_{rn} accounts for non-uniformity of the field in the transverse direction, including non-uniformities due to finite source size and collimator scatter. k_{h} is a correction for the humidity of the air and k_{ion} corrects for ion recombination. Other corrections might include corrections for the chamber stem or chamber holders.

The stopping power for graphite is strongly dependent on the value of *I*, the mean ionization energy, and the density (bulk density or grain density) used to calculate the density effect. ICRU 37 recommends a bulk density of 1.70 g/cm³ and an *I*-value of 78±7 eV (Ref. 46). More recent experiments indicate that the grain density (2.265 g/cm³) is more appropriate⁴⁷ and that a more accurate *I*-value is 86.8±1.2 eV (Ref. 48). The restricted stopping power ratio graphite to air will also depend on the choice of Δ (usually taken as the energy of an electron with a range in air equal to the mean chord length of the cavity). Changes to any of these quantities will affect $\overline{s}_{\text{gr,air}}$.

Most experiments determine W_{air} for electrons by comparing graphite calorimetry with ionization measurements from cavity ionization chambers to obtain the product $W_{air}\overline{s}_{gr.air}$. Previous re-evaluation of stopping powers and other correction factors led to W_{air} being changed from 33.85 eV (Ref. 49) to 33.97 eV (Ref. 50). If new changes are made to the stopping power ratios, W_{air} would again need to be reevaluated. As well, W_{air} is assumed to be independent of electron energy, but the validity of this assumption must be investigated more completely.

7.2.2 Ferrous sulphate-based absorbed-dose standards

When ferrous sulphate (Fricke) solution is irradiated, ferrous ions (Fe^{2+}) are converted to ferric ions (Fe^{3+}) through oxidation reactions. This produces a change in the optical density of the solution which can be measured using a spectrophotometer. Photon beam measurements are taken by filling small vials with Fricke solution and irradiating them in a water phantom. Based on the change in optical density of the solution, the absorbed dose to water from photon beams can be calculated according to:

$$D_{\rm w} = \frac{\Delta A_T}{\underbrace{\rho l}_{m}} \frac{1}{\underbrace{(\varepsilon_{\rm m} G)_T}_{C}} \underbrace{\frac{1}{a(\overline{\mu}_{\rm en}/\rho)_{\rm f,w} + b\overline{s}_{\rm f,w}}}_{\widetilde{R}_{\rm f}^{\rm W}} k_{\rm vial} k_{\rm dd} k_E.$$
(7.5)

In the above equation:

 ΔA = change in absorbance or optical density

T =temperature

 ρ = density of ferrous sulphate solution

l = optical path length

 $\varepsilon_{\rm m}$ = molar extinction coefficient

G = radiation-induced chemical yield

a =large detector coefficient

b = small detector coefficient

 $(\mu_{en}/\rho)_{fw}$ = ratio of mass energy absorption coefficients Fricke/water

 \overline{s}_{fw} = ratio of mean restricted stopping powers, Fricke/water

 $k_{\rm vial}$ = correction for vial walls

 $k_{\rm dd}$ = correction for non-uniformity of field

 k_E = correction for energy dependence of $\varepsilon_m G$

 k_{vial} and R_{f}^{w} have been investigated using both Monte Carlo simulation and analytical methods for photon energies between ⁶⁰Co and 24 MV (Ref. 51). The methods showed good agreement and indicated that for typical vials R_{f}^{w} shows almost no energy dependence. This is mainly a fortuitous result. As the energy increases, the detector shifts from behaving like a 'large' detector to behaving like a 'small' detector, reducing the effect of the decreasing mass energy-absorption coefficient ratio. k_{vial} is small (<0.4%) for plastic walls, but varies from 1.001 (⁶⁰Co) to 0.983 (24 MV) for Pyrex glass walls.

The product $\varepsilon_m G$ is easier to determine and more precisely known than the individual quantities. Generally this product is determined through comparison with calorimetry. Comparison of Fricke with water calorimetry⁵² indicated that $\varepsilon_m G$ shows an energy dependence of 0.7% between ⁶⁰Co and 20 MV photon beams (k_E =1.007).

Alternatively to using water calorimetry, the response of the Fricke solution can be calibrated using total absorption of electrons⁵³. The energy of electrons is verified in this method using a 180° bending magnet and slit apertures which are adjusted until the current measured at a Faraday cup is maximum. The number of electrons relative to the beam monitor is measured using the Faraday cup. When the bending magnet is turned off, the electron beam is completely absorbed in a volume of Fricke solution (see Figure 7.1). The absorbed dose to the Fricke solution has been determined and corrections are made for energy loss due to bremsstrahlung, back-scatter and interactions in the exit window, air and vessel wall. By measuring the change in optical density of the solution, a calibration coefficient (*C* in equation (7.5)) for the Fricke solution can be determined. The calibrated solution can then be used for dose measurements in other radiation beams.



Figure 7.1 Schematic diagram of the system used to calibrate the response of Fricke solution by the total absorption of electrons. The beam can follow two alternative paths, towards the Faraday cup or the Fricke solution, depending on whether the bending magnet in the deflection chamber is turned on or off. The position of the slits, B1 and B2 can be adjusted to determine the electron energy. A current transformer acts as a beam monitor. (Figure based on Ref. 53).

7.2.3 Calorimeter-based absorbed-dose standards

Calorimetry is the most direct method of measuring absorbed dose. The energy absorbed by a material, $D_{\rm m}$, is related to the change in material temperature, ΔT , according to the following equation:

$$D_m = \Delta T c_P \prod_i k_i , \qquad (7.6)$$

where c_P is the specific heat capacity of the material at constant pressure. Calorimetry has a distinct advantage over the other methods discussed because c_P (unlike W_{air} or $\varepsilon_m G$) can be measured without using a radiation field. There are two materials used for calorimeter-based standards of absorbed dose to water: water and graphite. In a water calorimeter, the D_m is dose to water, so no additional conversion is necessary, however, if the calorimeter medium is graphite there must be a process for conversion from dose to graphite to dose to water.

7.2.3.1 Graphite calorimetry



Figure 7.2 (a) The NPL high-energy photon beam absorbed dose graphite calorimeter. (b) Schematic drawing of the NPL calorimeter. (Figure taken from Ref. 3. Used with permission.)

An example of a graphite calorimeter is shown in Figure 7.2. In graphite calorimetry the absorbed dose to graphite, D_{gr} , is determined according to:

$$D_{\rm gr} = c_{\rm gr} \Delta T_{\rm gr} \prod_i k_i , \qquad (7.7)$$

where c_{gr} is the specific heat of the graphite calorimeter core and T_{gr} is the core temperature. Rather than using a reference value of c_{gr} , the heat capacity of the calorimeter core, C_{gr} , is usually measured directly by dissipating electrical energy in the core and monitoring the resulting temperature rise. Since

$$C_{\rm gr} = c_{\rm gr} m_{\rm gr} \tag{7.8}$$

then

$$D_{\rm gr} = \frac{C_{\rm gr}}{m_{\rm gr}} \Delta T_{\rm gr} \prod_i k_i \,. \tag{7.9}$$

Several factors must be corrected for to accurately determine the dose using a graphite calorimeter including:

- energy not converted to heat (heat defect), $k_{\rm HD}$
- conductive and radiative heat transfer from the core, $k_{\rm HT}$
- effects of vacuum gaps on dose distribution, k_{gap}
- presence of non-graphite materials in core
- non-uniformity of the dose distribution

 $k_{\rm HD}$ has been assumed to be unity for graphite. It has been measured by various authors in different radiation qualities and the results, although not inconsistent with no heat defect (2±2%, 0.38±0.61%, 0±0%) (Ref. 54), indicate that the uncertainty of $k_{\rm HD}$ (sometimes quoted as zero) should be assigned a value reflecting the spread and uncertainty of published values for the heat defect. A non-unity heat defect is possibly related to dissolved oxygen in the graphite and may be eliminated by preirradiation⁵⁵. As well, atomic displacements in the graphite crystal structure may also result in a heat defect.

Several methods can be used to control heat transfer in the calorimeter. The gap between the core and jacket is evacuated and material such as silk thread or Styrofoam beads can be used to hold the core in place. Surfaces of the jackets may be covered with aluminized Mylar foil to reduce radiative transfer. Three modes of operation can be used:

- quasi-adiabatic (jacket temperature is increased as core temperature increases)

- heat-loss compensated (signals from core and jacket are summed)

- quasi-isothermal (radiation power is replaced by an equal amount of electrical power, maintaining constant heat loss from the core)

Even with all of these measures, additional heat transfer corrections are necessary. Most of these can be determined using an equation of the form:

$$\frac{dQ}{dt} = -K\Delta T , \qquad (7.10)$$

where *Q* is the energy transferred, *t* is the time, *K* is the heat transfer coefficient and ΔT is the temperature difference between two bodies in the calorimeter.

The effect of the vacuum gaps on a ⁶⁰Co field has been studied using Monte Carlo simulations⁵⁶ and for high-energy photon beams (⁶⁰Co to 19 MV) using ionization chamber measurements⁵⁷. k_{gap} corrects for the difference in dose at the center of the core with and without gaps present in the graphite, where the center of the core is kept at a constant distance from the source and the thickness of graphite in front of the core is kept constant. These corrections can be significant, depending on the gap thickness and beam energy.

There are two methods for converting from absorbed dose to graphite to absorbed dose to water. The first is the photon fluence scaling method^{58,59} which presents a calculation-based conversion from dose to graphite to dose to water. This method is valid if Compton scattering is the predominant mode of interaction. The material dimensions and irradiation geometry are scaled by the inverse of the electron density of the material so that:

$$D_{\rm w} = D_{\rm gr} \left(\Psi\right)_{\rm gr}^{\rm w} \left(\frac{\overline{\mu}_{\rm en}}{\rho}\right)_{\rm gr}^{\rm w} \left(\beta\right)_{\rm gr}^{\rm w} \text{ and } \left(\Psi\right)_{\rm gr}^{\rm w} = \frac{f_{\rm gr}^2}{f_{\rm w}^2}, \qquad (7.11)$$

where f_{gr} and f_w are the distances from the source to the point of measurement in graphite and water respectively. All other terms are defined in the same way as in equation (7.4). Additional corrections are required for air attenuation, non-Compton interactions and finite source size.

The second method, which is measurement-based, is to transfer the absorbed dose in graphite to absorbed dose in water using an ionization chamber⁵⁸. There are two equations relating ionization measured by the chamber to absorbed dose, depending on whether the chamber wall is considered thin or thick relative to the range of electrons produced by the radiation beam. For a thick-walled chamber the relationship is:

$$D_{\rm w} = D_{\rm gr} q_{\rm w,gr} \left(\overline{\mu}_{\rm en} / \rho \right)_{\rm w,gr} \beta_{\rm w,gr} p_{\rm w,gr} , \qquad (7.12)$$

while for thin-walled chambers it is:

$$D_{\rm w} = D_{\rm gr} q_{\rm w,gr} \left(\frac{\overline{s}_{\rm w,air}}{\overline{s}_{\rm gr,air}} \right) p_{\rm w,gr} , \qquad (7.13)$$

where $q_{w,gr}$ is the ratio of the measured charge water/graphite, $p_{w,gr}$ is the ratio of the chamber perturbation corrections water/graphite and the other quantities have the same definitions as in equation (7.4). For thin-walled chambers, if the chamber-to-source distance is kept fixed while the depths of measurement in graphite and water are scaled by the inverse of the electron density, both the electron and photon fluence in the ionization chamber will be the same in each medium. (This assumes that Compton scattering is the predominant mode of interaction.) Therefore the stopping powers in air will be equal, leaving the ratio of restricted mass stopping powers water/graphite. A similar process can be followed if using Fricke as a transfer dosimeter⁶⁰.



Figure 7.3 Schematic diagram of the NRC sealed water calorimeter. (Figure taken from Ref. 3, used with permission).

7.2.3.2 Water calorimetry

As already discussed in section 7.1, although other types of water calorimeters have been built (open stagnant-water calorimeters, insulated small-volume calorimeters), the water calorimeters currently used for absorbed-dose standards are stagnant sealed water calorimeters like the one shown in Figure 7.3. These take advantage of the low thermal diffusivity of water to measure temperature rise at a point and multiply by the specific heat capacity of water to calculate the absorbed dose to water according to equation (7.1). Corrections must be applied for factors that affect the measured temperature or the radiation field. These include

 $k_{\rm HD}$, the chemical heat defect correction, discussed in section 7.1.2

- $k_{\rm HT}$, a correction for heat transfer by conduction and convection, discussed in sections 7.1.4.1 and 7.1.4.2
- *k*_P, a correction for perturbation of the radiation field caused by non-water materials,
- k_{dd} , a correction for non-uniformity of the dose profile when comparing the position of the thermistors to the reference point of measurement,

 k_{ρ} , the density correction factor to account for the density change in water between the calorimeter operation temperature and the temperature at which another detector is calibrated.

Water calorimetry has the advantage of measuring absorbed dose to water directly, so no conversion process is necessary. This is a significant advantage over graphite calorimetry. However, there are some disadvantages. The heat capacity of water is very high, therefore the temperature change in water is only 0.2 mK/Gy, six times smaller than graphite. Water calorimetry thus requires very sensitive methods for temperature measurement and measurements typically have a high standard deviation compared with graphite calorimetry measurements

7.3 CURRENT STATUS OF ABSORBED-DOSE STANDARDS

7.3.1 Photon beams

The ionization chamber-based method is used for the BIPM (Bureau International des Poids et Mesures) absorbed dose to water standard in ⁶⁰Co (Ref. 45). Graphite calorimeters are used as the absorbed dose to water standard for ⁶⁰Co at NPL (National Physical Laboratory) in the UK⁶¹, BNM-LNHB (Bureau National de Métrologie – Laboratoire National Henri Becquerel) in France⁶², ENEA (Ente per le Nuove technologie l'Energia e l'Ambiente) in Italy⁶³, BEV (Bundesamt für das Eich- und Vermessungswesen) in Austria⁵⁴, ARL (Australian Radiation Laboratory) in Australia⁵⁴ and NMi (Nederlands Meetinstituut) in the Netherlands⁵⁴. The NPL also uses their graphite calorimeter for establishing the absorbed dose to water in other high-energy photon beams⁶¹.

Water calorimetry is the standard for absorbed dose in ⁶⁰Co at NRC (National Research Council) in Canada²⁸ and at METAS (Metrologie und Akkreditierung Schweiz) in Switzerland³³. NIST (National Institute of Standards and Technology) has used both water and graphite calorimeters and currently uses water calorimetry for their absorbed dose to water standard in ⁶⁰Co (Ref. 54). The PTB (Physikalisch-Technische Bundesanstalt) in Germany recently switched from a total

absorption Fricke-based standard for absorbed dose to water in ⁶⁰Co to a water calorimeter standard³⁰. Both NRC and METAS also use water calorimetry as the absorbed dose to water standard for other high-energy photon beams^{32,33}. Other standard institutes are currently developing water calorimeters for ⁶⁰Co and photon beam absorbed dose to water standards (e.g., NMi (Ref. 43)) and NIST is currently working on further developing room-temperature water calorimetry⁶⁴.

7.3.2 Electron beams

Absorbed-dose standards for electron beams have only recently been developed. In 2002 METAS introduced a calibration service for 10 electron beam qualities between R_{50} =1.75 cm and 8.54 cm (Ref. 33). This calibration is based on a Fricke system. The Fricke solution is calibrated by the total absorption method for monoenergetic electron beams from 5.3 to 22.4 MeV, applying corrections for energy lost in the entrance and exit foils and through bremsstrahlung. Vials of this Fricke solution are irradiated in a water phantom correcting for vial effects and converting dose to Fricke to dose to water.

The National Physical Laboratory (NPL) in the United Kingdom introduced a calibration service for electron beams in 1998 (Ref. 65). These calibrations are based on a graphite calorimeter standard for electron beams with nominal energies from 4 to 19 MeV. A set of NACP-02 chambers are calibrated in graphite and then measurements are taken in water. The conversion from absorbed dose to graphite to absorbed dose to water is done using equation (7.13).

Currently there are no electron beam standards for absorbed dose to water based on water calorimetry.

7.3.3 Comparisons between the methods

Both water and graphite calorimeters can currently achieve an overall uncertainty on absorbed dose to water in ⁶⁰Co on the order of 0.4% (Ref. 3). The uncertainty for water calorimetry is primarily due to heat defect while the graphite calorimeter

uncertainty is primarily from the conversion from dose to water to dose to graphite. Fricke dosimetry has a larger uncertainty (0.7%) (Ref. 66). The BIPM ionization chamber absorbed dose standard has an uncertainty of 0.4% (Ref. 45).

Fricke and ionization chamber methods are less absolute than calorimetry methods since a radiation field is required for determining their conversion coefficient, (*C* in equation (7.3)), (W_{air}/e or $\varepsilon_m G$), and this coefficient in some cases is not independently determined (many evaluations are based on calorimetry). Water calorimetry has an advantage over graphite calorimetry as it does not require conversion from absorbed dose to graphite to absorbed dose to water.

Inter-comparison between national standards for absorbed dose to water is an important method of maintaining international consistency. Indirect comparisons using ionization chambers as transfer instruments have been carried out (e.g. Ref. 44,66). Maintaining a variety of types of absorbed dose standards is advantageous, therefore, as inter-comparison of various methods can give greater confidence in each individual method. This is an advantage of absorbed dose standards over air kerma standards, which are all based on graphite ionization chambers.

7.4 THE ROLE OF WATER CALORIMETRY IN ABSORBED-DOSE BASED CALIBRATION PROTOCOLS

Absorbed-dose based protocols such as TG-51 (Ref. 67) and TRS 398 (Ref. 68) are widely used in clinical reference dosimetry for megavoltage photon and electron beams. To simplify the discussion, I will follow the form and notation of TG-51, but the approach of TRS-398 is very similar. The TG-51 protocol is based on calibration of an ionization chamber in a ⁶⁰Co beam in terms of absorbed dose to water, providing an absorbed dose to water calibration coefficient, $N_{D_u}^{60}$ for the chamber. For photon and electron beams, the absorbed

dose calibration coefficient at beam quality Q, $N_{D_w}^Q$, is related to $N_{D_w}^{6^0C_0}$ by the following equation:

$$N_{D,w}^{Q} = k_{Q} N_{D,w}^{60\,\text{Co}} \quad , \tag{7.14}$$

where k_Q is the beam quality conversion factor. In TG-51, k_Q for electron beams is rewritten as the product of k_{ecal} and $k'_{R_{50}}$, the photon-electron conversion factor and the electron beam quality conversion factor respectively. k_Q values provided in the protocols are calculated from mass collision stopping powers, *s*, and chamber perturbation corrections, *p*, according to:

$$k_{Q} = \left(\frac{\overline{s}_{\text{w,air}}p}{\overline{s}_{\text{w,air}}p}\right)_{{}^{60}Co}^{Q}$$
(7.15)

For photon beams, measurements have been performed to directly measure k_Q and confirm the validity of these factors using water calorimetry³⁴⁻³⁷, however, for electron beams, many of the quantities used to calculate k_Q are based on simplified models and calculations and have not been directly measured.

7.5 MOTIVATION FOR THIS WORK

Recent measurements^{69,70} and Monte Carlo simulations⁷¹⁻⁷⁵ indicate that there may be errors in some of the factors used in calculating k_Q for electron beams in the current protocols. One example is work by Buckley and Rogers⁷², which indicates that p_{wall} , a perturbation factor used to calculate the electron beam quality conversion factor and which was assumed to be unity for cylindrical chambers in electron beams, may have values of up to 1.006. Verhaegen et al.⁷⁴ performed Monte Carlo studies of the perturbation corrections for the NACP-02 plane-parallel chamber in water, which were also previously considered to be unity. They found that at the reference depth in water, d_{ref} , p_{wall} may have values of up to 1.023 and p_{cav} may be as small as 0.992, so that the product of the perturbation factors exceeded unity by 0.2 to 1.5% depending on the electron beam calibration service based on graphite calorimetry, as the perturbation corrections

for the NACP-02 chamber are used in converting absorbed dose to graphite to absorbed dose to water. There also remain uncertainties about the perturbation corrections in graphite for this chamber ⁷⁶.

The advantage of using water calorimetry rather than graphite calorimetry or Fricke dosimetry for measurements in electron beams is that it provides a direct measurement of absorbed dose to water in water without the need for energydependent conversion or correction procedures. Hence, there remains the need to develop a water calorimetry system that is sufficiently accurate and precise for electron beam absorbed dose determination over a wide range of energies. This means that not only water quality and thermal defect are issues for consideration, but also the effects of thermal gradients need to be properly taken into account.

There are two goals of applying water calorimetry to electron beam absorbed dose to water measurements. The first is to obtain measured values of k_Q for various chambers in electron beams in order to determine the accuracy of values included in current dosimetry protocols. The second is ultimately to establish absorbed dose to water standards using water calorimetry. These can be compared with graphite calorimeter and Fricke-based standards and can be used to provide direct calibration of clinical ionization chambers in electron beams, rather than relying on conversion from ⁶⁰Co calibration.

Some early efforts were made to use a first-generation open water calorimeter for a wider range of electron beam measurements¹⁰. In these measurements, however, water purity was not carefully controlled, so that the chemical heat defect was uncertain. As well, the effect of temperature gradients produced by electron beams was not corrected for. Water calorimetry in low energy electron beams was generally considered unfeasible since high dose gradients were thought to provoke unmanageable temperature gradients.

In this work, we present the Electron Sealed Water (ESW) calorimeter, a new calorimeter designed specifically for measurements in clinical electron beams. We also discuss the determination of various correction factors necessary for these calorimetry measurements and finally use water calorimetry measurements to evaluate beam quality conversion factors for two different ionization chambers, the Exradin A12 cylindrical chamber and the PTW Roos plane-parallel chamber, for electron beam energies between 6 and 20 MeV.

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Chapter 8

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8.1 THE ESW CALORIMETER

The ESW calorimeter (see Figure 8.1 and Figure 8.2) has been designed to be relatively compact and transportable. The calorimeter box contains a $30 \times 30 \times 20$ cm³ water phantom with 10 mm thick PMMA walls. The calorimeter is operated at 4°C to avoid convection in the water. This operating temperature is achieved and maintained by surrounding the water phantom with a cooling and insulating system consisting of a 5 cm layer of Styrofoam, 5 mm copper plate with copper tubing soldered to it and a second 5 cm layer of Styrofoam. This is

enclosed in a plywood box which has outer dimensions of $55 \times 55 \times 40$ cm³. The lid consists of a 5 mm copper plate with copper tubing soldered to it and Styrofoam layers of 2.5 and 1 cm above and below the copper respectively. A window is cut in the copper of the lid to allow for irradiation from above by a 10×10 cm² beam. This window is covered with a 0.1 mm thick brass foil to provide active cooling of this area.

To cool the calorimeter, we used a Neslab RTE-7 refrigerated bath/circulator (Thermo Scientific). This was filled with cooling fluid (Motomaster Long-life antifreeze/coolant, Canadian Tire) and the bath controls the temperature of the cooling fluid to within 0.1°C and circulates it through insulated flexible plastic tubing which is attached to the copper tubing in the calorimeter box and lid. A valve can also be opened to allow the cooling fluid to flow through an anodized aluminum heat exchanger inside the water phantom when large temperature adjustments are required (e.g. when reducing the temperature of the water from room temperature to 4°C). With the valve closed, the water phantom temperature can be maintained within 5 mK over several hours, which is important as the temperature change produced by irradiation is only 0.24 mK/Gy.

There is a magnetic stirrer (Corning, 84302) at the bottom of the water phantom which is used during initial cooling as well as following a series of measurements to remove temperature gradients produced by irradiation. The stirrer has a 5 cm long Teflon-coated magnetic bar which is placed inside the water phantom. This is turned by a circular magnet underneath the Styrofoam mounted on a rotating shaft and driven by a motor underneath the copper plate.

On the side of the water phantom is a depth-positioning device for the calorimeter vessel and the ionization chambers. This is composed of two Delrin brackets attached to the side of the phantom with stainless steel screws. Between the brackets are two smooth stainless steel rods with a threaded stainless steel rod between them. The positioning bracket, also made of Delrin, runs along these

rods and can be raised or lowered by turning the threaded rod. This is done using an aluminum knob that is removed from the rod end before putting on the calorimeter lid. The holder for the calorimeter vessel or ionization chamber is screwed on to the positioning bracket with three stainless steel screws. A stainless steel ball bearing is used to provide a pivot point for the vessel or chamber holder so that the screws can also be used to level the chamber or vessel.

The depth of the vessel or chamber is measured using waterproof digital calipers (Mitutoyo, 500-652) mounted on a PMMA support that is then screwed to an aluminum bracket. The bracket can be placed on the top edge of the PMMA phantom walls so that the pointer of the caliper is aligned with the center of the vessel. The caliper is opened so that the pointer just touches the water surface and then just touches the vessel or chamber surface and the difference between the measurements at these two points indicates the depth. After the depth is set, the bracket is removed before putting on the calorimeter lid.



Figure 8.1. Schematic diagram of the ESW calorimeter.



Figure 8.2 Photograph of the ESW calorimeter taken from above with the lid removed.

8.1.1 Glass vessel

The calorimeter vessel (see Figure 8.3) is made of Pyrex glass and is of a "pancake" cylindrical design. The front and back circular windows are 79 mm in diameter and 1.1 mm thick and the cylindrical side wall is 2.1 mm thick. The internal separation between the front and back windows is 24 mm. There are two ports in the side wall with threaded openings for the insertion of the thermistor probes. A third port is used for filling and gas bubbling and has a small glass bulb in which a gas bubble can be trapped to allow for volume changes in the water. This port is closed using a glass stopcock with three CAPFE[®] Teflonencapsulated O-rings. A threaded plastic cap holds the stop-cock in place.



Figure 8.3 Schematic diagram of the ESW calorimeter vessel and thermistor probes.

8.1.2 Thermistor probes

The thermistor probes were constructed using Pyrex tubing with a diameter of 8 mm and a wall thickness of 1 mm which was pulled down on one end to an outside diameter of approximately 0.6 mm over a length of 4 cm and an inside diameter of at least 0.3 mm and the end was closed. Glass-coated bead thermistors (NTC BR11 Thermobead, Thermometrics) were inserted into the Pyrex tubing, approximately 0.7 mm from the tip of the sealed end. These thermistor beads are 0.25 mm in diameter and have a nominal resistance of 10 k Ω at 4°C. The thermistor leads are 7.9 mm long and made of a platinum alloy.

These leads are soldered to the two leads from a foil-shielded twin-lead cable (Belden 9452). To provide strain relief, the cable leads are fixed to the side of the glass tubing using epoxy glue. For the portion of the cable within the Pyrex tube, the cable coating and foil shield are removed. Waterproofing is provided using latex tubing which is stretched over the large end of the glass tube and extends outside the water phantom.

8.1.3 Electronics

Three PT-100 RTD temperature probes (Thermo Kinetics, R21-D100E4) are used to monitor the water and copper temperature: two in the water phantom and one on the copper plate. The resistance of each probe is read using the 4-wire ohmmode of a Keithley K2000 digital multimeter. The wires from the thermistors are connected to an AC bridge circuit (see Figure 8.4). The sinusoidal excitation voltage (1 V, 10 Hz) is provided by a SR510 lock-in amplifier (Stanford Research Systems) which is also used to measure the output voltage from the bridge. This output voltage is related to the resistance change of the thermistors. All connections are made using coaxial cables. We used two different bridge circuits in our measurements, a passive bridge containing only resistors and capacitors and an active bridge which also uses operational amplifiers (op-amps).

8.1.3.1 The passive AC bridge

In the passive AC bridge (Figure 8.4) one arm of the bridge is composed of two 20 k Ω Zeranin resistors (Burster) while the other arm has the two thermistors and is balanced using a Burster 1408 high-precision resistance decade box. The lockin amplifier measures the voltage of each arm of the bridge (points A and B) and provides the difference between the two voltages as output. Capacitors are included in the bridge circuit to balance the capacitive component of the output signal.



Figure 8.4 Schematic diagram of the passive AC bridge circuit.

8.1.3.2 The active AC bridge

The active AC bridge circuit is shown in Figure 8.5. The major difference with this bridge is that the two sides of the voltage divider are powered by a perfectly out of phase signal. Hence, there is no need for the fixed resistor signal and point B is directly connected to ground. This is accomplished using two OP177 op-amps (Analog Devices), the first is used as a zero gain amplifier and the second functions as a voltage inverter. The op-amps are powered by a +/- 15 V power supply (Syston-Donner, TL8-3). The bridge also contains four 10 k Ω Zeranin resistors (Burster) and additional resistors are used in combination with the op-amps. The other arm of the bridge contains the thermistors and the decade resistor box. The lock-in amplifier reads the voltage at point A while point B is grounded through the power supply ground. In order to avoid ground loops, all cable shields and the bridge box are also grounded through this one point. There are points where a decade capacitor box (IET Labs, CSH4-10pf-WC) can be added to the circuit to balance the capacitive component of the signal.



Figure 8.5 Schematic diagram of the active AC bridge circuit

8.1.4 Software

Computer software is used to remotely control and read the lock-in amplifier and the digital multimeter through a GPIB interface and the bath through an RS232 interface. Three programs were used in this work. The original software was developed by Togane and Seuntjens (1997) for the NRC water calorimeter system and we made modifications to adapt the software for use with our equipment which is different from what is used in the NRC system.

8.1.4.1 ProbeCal

The ProbeCal software is used for the calibration of the RTD PT-100 temperature probes and the thermistor probes. This software controls the bath and the digital multimeter. Information used in the ProbeCal program including RTD calibration parameters and conditions for determining temperature stability is provided in the ProbeCal.par parameter file

8.1.4.2 H2ORun

The H2ORun software is used when performing measurements with the ESW calorimeter. It controls the lock-in amplifier and digital multimeter as well as receiving timing information from a Keithley 6517A electrometer. There are three modes of operation for this software: run mode, ohm-calibration mode and idle mode. Run mode is used when measuring temperature change in the calorimeter due to irradiation. Ohm calibration mode is used to calibrate the AC bridge response to a 1 Ω resistance change. Idle mode allows the copper and water temperatures to be monitored using the RTD probes and the bridge voltage to be measured continuously. This mode is used to determine when the calorimeter temperature is at 4°C and stable. Information, including default settings and thermistor and RTD probe calibration parameters, is provided to the H2ORun program by the H2OSetup.par parameter file.

8.1.4.3 H2OView

The H2OView software performs analysis on the output files from H2ORun. It can be used to analyze run or ohm calibration data in batches and gives statistical information on each batch as well. H2OView also uses the calibration and default setting information from the H2OSetup.par parameter file.

8.1.5 Chart recorder

To assist in monitoring the calorimeter temperature, a x-t paper chart recorder (Soltec, 1242) is used to plot the output signal from the lock-in amplifier. Although the data from this chart recorder is rarely used in analysis, it is helpful

as a visual tool for monitoring temperature drifts within the calorimeter and for following the long-term behaviour of the calorimeter.

8.2 IONIZATION CHAMBERS

Two ionization chambers were primarily used in this study: the Exradin A12 cylindrical chamber (SN 310) and the PTW Roos plane parallel chamber (SN 273) which were described in section 2.3. The readings from each of these ionization chambers were measured using a Keithley 6517A electrometer (SN 0790027). The current measurement of this electrometer was calibrated at NRC. The Exradin A12 chamber has an absorbed dose to water calibration in ⁶⁰Co established at NRC. The PTW Roos chamber was cross calibrated against the Exradin A12 chamber in the 20 MeV electron beam of a Varian Clinac 21EX to obtain the product $k_{ecal}N_{D_w}^{60Co}$ for this chamber.

To monitor any variations in accelerator output during the course of calorimeter and ionization chamber measurements, a third ionization chamber, a NE 2571 cylindrical chamber (Bicron-NE), was used along with a Solid Water sleeve. A 5 cm thick Delrin block was cut to fit in the 10×10 cm² applicator for the Clinac 21 EX. This block has a hole drilled in it to allow the Solid Water sleeve with the NE 2571 chamber to be inserted.

8.3 PREPARING THE VESSEL AND PROBES FOR MEASUREMENTS

When preparing for measurements, the two thermistor probes are positioned inside the glass vessel with a 5 mm separation between the tips. CAPFE[®] Teflonencapsulated O-rings and threaded Teflon bushings are used to seal each thermistor probe in a vessel port. Four screws on each bushing allow for small adjustments of the probe angles. The distance from the front of the glass vessel window to each thermistor bead is measured using a traveling microscope which has a vernier scale which can be read to the nearest 0.01 mm. This is done by focusing first on the front of the glass, then lowering the microscope until the
thermistor bead is in focus and reading the distance the microscope is lowered. A correction of 0.35 mm is applied for the effect of the index of refraction of the glass. The uncertainty on the position based on one standard deviation of 10 measurements using this method is ± 0.3 mm.

The vessel is rinsed and filled with high-purity water from a MilliQ-UV Plus (Millipore) water purification system (total organic content <5 ppb). The glass stopcock is backed off part way so that the gas bubbling port is open but the main filling port remains sealed. A small Teflon tube is inserted through the bubbling port and is used to bubble the water in the vessel with either high-purity nitrogen or hydrogen gas (Alphagaz, <2 ppm O₂) for 3 to 4 hours to remove other dissolved gases. This tube is then removed and the vessel is sealed by completely closing the glass stopcock, ensuring that a small bubble of gas is trapped in the glass bulb.

A PMMA ring is attached to the vessel using three Delrin brackets and nylon screws. The ring is fixed to the depth-positioning bracket in the water phantom. The level of the vessel can be adjusted so that the front face is parallel with the water surface. Once the vessel is placed in the water phantom the water temperature is reduced to 4° C.

8.4 MEASUREMENTS UNDER THE CALORIMETER LID

Since the lid adds material in the path of the radiation beam, it was necessary to perform measurements to determine the effect of this material on the beam parameters.

Measurements were performed on the Varian Clinac 21EX. The lid was mounted using aluminum brackets above an RFA-300 3D scanning water tank (Scanditronix-Wellhofer). The tank was positioned so that the top of the lid was at 100 cm SSD and the water level was at 105.6 cm SSD, since these are the conditions present in the calorimeter measurements. For the electron beam measurements, the $10 \times 10 \text{ cm}^2$ applicator was inserted above the lid with a $10 \times 10 \text{ cm}^2$ cut-out.

PDD measurements were taken for each photon and electron beam. As well, in-plane and cross-plane profiles were taken at several depths for each beam, including the reference depths, to examine beam flatness. These measurements were performed with diodes. The EFD-3G and PFG-3G diodes (Scanditronix-Wellhofer) were used for electron and photon beams, respectively. An additional diode was placed in the corner of the field above the lid to monitor variations in accelerator output.

8.5 DETERMINING THE ABSORBED DOSE TO WATER

As described in section 7.1, the absorbed dose to water can be determined by water calorimetry according to the simple equation:

$$D_{\rm w} = c_{\rm w} \Delta T_{\rm w} \prod_i k_i , \qquad (8.1)$$

where D_w is the absorbed dose to water, ΔT_w is the change in water temperature, c_w is the specific heat capacity of water and k_i are correction factors.

8.5.1 Specific heat capacity of water

The specific heat capacity of water changes as a function of temperature (see Figure 8.6). At 4°C it has a value of 4.205×10^3 J·kg⁻¹·K⁻¹ (Ref. 1).



Figure 8.6 Specific heat capacity of liquid water at 100 kPa constant pressure as a function of temperature (Ref 2).

8.5.2 Determining ΔT

There are several steps involved in determining the change in water temperature for the ESW calorimeter system. Since the system obtains a signal in volts, the voltage change must be related to a fractional resistance change which must in turn be related to a temperature change. Several calibrations are therefore necessary: calibration of RTD probes, calibration of thermistor probes, and calibration of the AC bridge.

8.5.2.1 Calibration of the RTD probes

The PT-100 RTD probes were calibrated against a NIST-traceable calibrated mercury thermometer. The calibration was performed in the circulating chiller over a range of temperatures between -4°C and 12°C at intervals of 1°C. The resistance of the RTD probes was measured at each temperature in 4-wire resistance mode using a Keithley 2000 digital multimeter. The chiller and

multimeter were operated via RS-232 and GPIB communication respectively using the ProbeCal software. The thermometer has divisions of 0.1°C and the temperature was read manually to the nearest 0.03°C. Readings of the temperature and resistance were taken once the temperature change in the bath was less than 10 mK/min and the resistance change was less than 0.005%. 15 resistance measurements were averaged for each temperature point for each probe. A linear fit was applied to the resistance as a function of temperature for each probe. This calibration procedure was repeated 2 to 4 times for each probe over a period of several months. Calibration parameters for each probe were included in the ProbeCal.par and H2OSetup.par parameter files.

8.5.2.2 Calibration of the thermistor probes

Using the calibrated RTD probes to determine the temperature, the thermistor probes were calibrated in the circulating chiller over a range of temperatures between -4°C and 12°C at intervals of 1°C. The ProbeCal software was again used to control the chiller and the digital multimeter. The RTD resistance was measured in 4-wire resistance mode, while the resistance of the thermistors was measured using 2-wire mode.

Once the temperature change measured with the PT-100 probes was less than 0.4 mK/min and the variation of the resistance was less than 0.005%, 15 resistance readings were averaged for each thermistor. The 1 Ω resistance of the lead wires was subtracted to obtain the thermistor bead resistance and the temperature was corrected for the thermistor bead power dissipation. The correction for power dissipation was small (<3mK) since the current used during calibration on the 200 k Ω range was only 10 μ A and the power dissipation of the thermistor bead is typically 2 mK/ μ W. This offset temperature does not change significantly as a result of temperature changes due to irradiation. The resistance of each thermistor probe as a function of temperature was fit to an equation of the form:

$$\ln R = a_0 + \frac{a_1}{T} + \frac{a_2}{T^2}.$$
(8.2)

From the relationship:

$$R = R_0 \exp\left[\beta \left(1/T - 1/T_0\right)\right],$$
(8.3)

it can be found that:

$$\beta(T) = a_1 + \frac{2a_2}{T} \tag{8.4}$$

and

$$R_0(T) = \exp\left[a_0 + \frac{\beta(T)}{T_0} - \frac{a_2}{T^2}\right],$$
(8.5)

where T_0 is 22°C in our case, and a_0 , a_1 and a_2 are constants of the linear fit. Values of β and R_0 were calculated for each thermistor probe. This calibration was performed 2 to 4 times for each probe over a period of several months. The calibration parameters were included in the H2OSetup.par parameter file.

8.5.2.3 Calibration of the AC bridge

When using the calorimeter for dosimetry, what is measured is the voltage change of the AC bridge signal. This voltage difference, measured by the lock-in amplifier, corresponds to a fractional change in the resistance of the thermistor probes as their temperature changes. Alternatively, a voltage difference can be produced by changing the resistance of the decade box. Calibration of the voltage change of the AC bridge for a given resistance change was therefore performed by increasing the decade box resistance by 1 Ω and measuring the change in output voltage on the lock-in amplifier.

The calibration was carried out using the ohm-calibration mode of the H2ORun software which monitors the voltage output from the lock-in amplifier and also reads the temperature of the water from the RTD probes. Calibration data for the probes is provided to H2ORun from the H2OSetup.par parameter file. The voltage is measured for 50 s, following which the resistance on the decade box is

manually increased by 1 Ω . 50 s afterwards the resistance is decreased by 1 Ω and the voltage is measured for a final 50 s. Using the ohm calibration mode of the H2OView software, a linear fit is applied to the combined initial and final 50 s of the measurement and a second linear fit is done to the 50 s where the resistance was increased. The 5 s before and after the resistance is switched are discarded to remove points where the bridge is adjusting to the change in voltage and to account for any effects of reaction time for the manual switching. The difference between the voltages obtained by the two linear fits is taken at the mid-point of the measurement. These 1 Ω calibrations were performed along with each set of calorimeter measurement temperature as well as to watch for any gain changes in the system. The results of the 1 Ω calibration as a function of temperature were included in the H2OSetup.par parameter file.

8.5.2.4 Analysis of calorimeter measurements

Once these calibration steps have been completed, it is possible to perform calorimeter measurements and convert the measured voltage change into a change in the water temperature. Combining these measurements with the specific heat capacity of water, from section 8.5.1, and the correction factors, which will be discussed in section 8.5.3, gives the absorbed dose to water at the position of the thermistor probes.

Calorimeter measurements are taken using the run mode of the H2ORun software. This reads the temperature of the water at the beginning and end of each measurement run based on the RTD probes via the digital multimeter and also monitors the voltage output of the lock-in amplifier during each run. The calibration parameters are provided via the H2OSetup.par parameter file. The number of monitor units delivered during irradiation and the setting of the decade resistance box are input by the user for each measurement run.

Each calorimeter measurement run is divided into three segments: the preirradiation drift, irradiation, and post-irradiation drift periods. The lengths of each of these periods can be altered by the user. The H2OView software is used to analyze each measurement run based on the voltage data and other run parameters as well as the calibration data from the H2OSetup.par parameter file. In H2OView a straight line is fit to each portion of the run. The fits to the pre- and post-irradiation drift periods are extrapolated to the time at the mid-point of the irradiation period. The amount of data from the pre-and post-drift regions used in determining the linear fit can be adjusted by varying the offset times. Generally the 10 s before irradiation and 20 s after irradiation are excluded from the data used in the fit. The voltage change is determined from the difference between the extrapolated values of each line at the mid-irradiation time. Using the temperature measured with the RTD probes and the AC bridge calibration parameters in the H2OSetup.par file, the voltage change is converted into a resistance change.

From equation (8.3), the temperature change ΔT that will result in a given resistance change ΔR for one thermistor can be expressed as:

$$\Delta T = \frac{\Delta R}{R} \frac{T^2}{\beta} \left(1 + \frac{\Delta R}{2R} + \dots \right).$$
(8.6)

The second order and higher terms can typically be neglected since $R >> \Delta R$. Therefore:

$$\Delta T = \frac{\Delta R}{R} S^{-1} \text{ where } S = \frac{1}{R} \frac{dR}{dT} = -\frac{\beta}{T^2}.$$
(8.7)

For two thermistors the situation is similar. In this case:

$$\Delta \overline{T} = \frac{\Delta (R_1 + R_2)}{R_1 + R_2} \overline{S}^{-1} \text{ where } \overline{S} = \frac{R_1 S_1 + R_2 S_2}{R_1 + R_2}.$$
(8.8)

Multiplying this temperature change by c_w and dividing by the number of monitor units delivered gives the absorbed dose to water per monitor unit at the thermistor position. Correction factors must still be applied to this value, however, and these corrections will be discussed in section 8.5.3.

8.5.3 Correction Factors

8.5.3.1 Density correction k_{ρ}

As discussed in section 7.1.4.1, to avoid convection, calorimeter measurements are performed with water at 4°C. Ionization chamber measurements, however, are done in room temperature water, approximately 22°C. Since the density of water changes slightly between 4 and 22°C (see Figure 8.7), a correction must be applied. The difference in density can be considered effectively a difference in depth, and the PDD measurements from section 8.4 can be used to calculate the effect of such a depth change to determine the value of k_{ρ} .



Figure 8.7 Density of liquid water at 100 kPa constant pressure as a function of temperature (Ref 2).

8.5.3.2 Chemical heat defect correction, k_{HD}

The chemical heat defect correction (discussed in section 7.1.2), k_{HD} , accounts for heat lost or gained due to radiation-induced chemical processes occurring within the calorimeter vessel. This correction will depend on the water purity as well as

the gases dissolved in the water. We used both a nitrogen-saturated and a hydrogen-saturated pure water system in this work, as described in section 8.3.

For a nitrogen-saturated pure water system, $k_{\rm HD}$ has been determined to reach a steady state of 1.000±0.003 once a sufficient accumulated dose is reached³. The hydrogen-saturated pure water system is also predicted to reach a steady state with $k_{\rm HD}$ equal to 1.000±0.003 and is less sensitive to any organic impurities which may be present in the water³.

8.5.3.3 Vessel perturbation correction, $k_{\rm P}$

The presence of the glass vessel perturbs the radiation field, causing both attenuation and scatter of the incident radiation. In order to determine the dose to water in the absence of the glass vessel, a vessel perturbation correction factor, $k_{\rm P}$, must be applied. The perturbation of the radiation field caused by the glass vessel was determined using the EGSnrc/dosrznrc Monte Carlo code⁴. Simulations were done, including the lid materials, both with and without the glass vessel for each beam. The dose scoring region at the point of interest had a 1 cm radius and 1 mm thickness. $k_{\rm P}$ is then calculated by taking the ratio of the dose without the vessel to the dose with the vessel at the position of the thermistor probes.

8.5.3.4 Conductive heat transfer correction, $k_{\rm HT}$

Since the calorimeter is operated at a temperature of 4°C, where the density of water is close to maximum, thermal perturbations resulting from convection in the water are negligible and can be ignored. Radiative heat transport is also negligible. However, a correction must still be applied for thermal conduction in the water resulting from temperature gradients. These temperature gradients arise from two main sources: the dose gradient of the radiation field and, since glass has a lower heat capacity than water, increased heating of the glass in the vessel and thermistor probes.

Heat transfer due to conduction can be expressed through the following partial differential equation:

$$\rho c \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q, \qquad (8.9)$$

where ρ is the density (kg/m³), *T* is the temperature (K), *t* is the time (s), *k* is the thermal conductivity (W·m⁻¹·K⁻¹) and *Q* is the energy deposition rate (W/m³). *Q* due to irradiation can be determined from the absorbed dose according to:

$$Q = \dot{D}\rho , \qquad (8.10)$$

where \dot{D} is the dose rate (Gy/s).

COMSOL MULTIPHYSICS (formerly FEMLAB) finite element modeling software was used to simulate the geometry, materials and irradiation heating present in our system and solve the conductive heat transport equation at the thermistor bead position (see Figure 8.8). The vessel was modeled without including the filling or thermistor ports. This provided a symmetric situation so that only ¹/₄ of the geometry needed to be used in the model and symmetry conditions could be applied to obtain the solution for the complete geometry. The dose in this geometry was determined from PDD measurements in water under the calorimeter lid, described in section 8.4, and corrected for the effects of non-water materials using the Monte Carlo simulations described in section 8.5.3.3. For the temperature modeling we assumed a flat 10×10 cm² radiation field for the electron beams and for the photon beams we added the beam divergence based on a 10×10 cm² field at 100 cm from the source and a 105.6 cm distance to the water surface.



Figure 8.8 Geometry used in COMSOL MULTIPHYSICS to model heat transfer by conduction. ¹/₄ of the complete geometry was modeled with symmetry conditions imposed along the two front planes in this view.

The temperature evolution was followed for a series of ten successive simulated irradiations including associated pre- and post-irradiation drift periods. Analysis of the simulations was similar to the measurement analysis: the temperature drift before the simulated irradiation was fit to a straight line and the irradiation and post-irradiation temperatures were normalized to this linear fit. By dividing by the expected temperature change in the absence of conduction, the amount of conductive heat transfer was determined. The normalized temperature difference in the same post-irradiation interval used for analyzing the measurements was fit with a straight line and this was extrapolated to the mid-irradiation time. This

gave the amount of conductive heat transfer we would expect to be present in our measurements and therefore the inverse of the extrapolated value provided the correction k_{HT} . This process was repeated for each of the ten simulated runs and an average of the corrections was used.

The consistency of the heat transfer corrections was evaluated by testing them for each of the different irradiation and drift times used in the electron and photon beam measurements (see section 8.6). As well, the simulated post-irradiation drift curves were compared with those obtained in our measurements.

8.6 CALORIMETER MEASUREMENTS

8.6.1 Electron beams

Calorimeter measurements were done on a Varian Clinac 21EX for 6, 9, 12, 16 and 20 MeV electron beams with a distance from the source to the water surface of 105.6 cm. The field size was set to 10×10 cm² at 100 cm SSD using a cut-out in the electron applicator (see Figure 8.9). R_{50} for each electron beam energy was determined from the PDD measurements under the calorimeter lid described in section 8.4. d_{ref} was calculated based on these values of R_{50} and the calorimeter vessel was positioned with the thermistor probes at d_{ref} . This was ensured by measuring the depth of the front face of the vessel below the surface of the water.

Irradiations of 667 MU at 1000 MU/min resulted in an irradiation time of 40 s and a dose of 5.5 to 6 Gy at the measurement point. For the 6, 12 and 20 MeV beams, measurements were also taken for 20 s irradiations, with 333 MU delivered at the 1000 MU/min rate. For the 6 MeV beam, measurements were taken for 80 s irradiations as well (1333 MU at 1000 MU/min). The temperature drift was measured for 60 s before each irradiation (pre-drift) and 90 s afterwards (post-drift). Runs were analyzed using the method described in section 8.5.2.4. Sets of 8 to 12 irradiation measurements were run and at least two 1 Ω bridge calibrations were performed for each set.



Figure 8.9 Photograph showing the ESW calorimeter set up for measurements of the Clinac 21EX electron beams. To the right is the Neslab RTE-7 refrigerated bath/circulator and the SR510 lock-in amplifier.

8.6.2 Photon Beams

For the photon beam measurements, the same basic procedure was followed, but adjustments were made to the depth and the irradiation and drift times. For the 6 and 18 MV beams, a depth of 8 cm was used rather than the usual reference depth of 10 cm, as 8 cm was the largest depth that could practically be achieved with our set-up. Measurements for the 6 MV beam were also done at 5 cm, the reference depth used for ⁶⁰Co measurements, and at 2 cm, the reference depth used for the 9 MeV electron beam measurements. These other depths were used to investigate whether there were depth-dependent effects in the calorimeter

measurements. For the Clinac 21EX beams, the SSD was 105.6 cm and the field size was 10×10 cm² at 100 cm SSD, so that at the water surface it was 10.56×10.56 cm². The maximum dose rate setting for photon beams on this linear accelerator is 600 MU/min, so this was used for 6 and 18 MV irradiations. Measurements were also performed in a ⁶⁰Co beam from a T-780 unit (see Figure 8.10). In this case, the SSD was 67 cm and the field size was 12×12 cm² at 80 cm SSD, making it 10.05×10.05 cm² at the water surface. The dose rate was approximately 1 Gy/min at the measurement depth in the ⁶⁰Co beam. The photon beam runs were analyzed with the H2OView software using the method described in section 8.5.2.4. Sets of 8 to 10 irradiation measurements were taken along with their associated drifts. All of the timings and depths used for each photon beam are listed in Table 8.1. At least two 1 Ω bridge calibrations were performed before each set.



Figure 8.10 Photograph of the ESW calorimeter set up for measurements of the T780 60 Co beam.

Beam	depth (cm)	pre-drift time (s)	irradiation time (s)	post-drift time (s)
6 MV	2	180	40	180
		180	100	180
	5	180	40	180
		180	180	180
	8	60	40	90
		60	67	90
		60	100	90
		180	10	180
		180	20	180
		180	40	180
		180	100	180
		180	180	180
18 MV	8	60	50	90
		60	100	90
		60	200	90
		180	100	180
⁶⁰ Co	5	180	180	180

 Table 8.1
 Depth of measurement and timing parameters used for calorimeter

 measurements in photon beams.

8.7 IONIZATION CHAMBER MEASUREMENTS

Ionization chamber measurements were done with the PTW Roos and Exradin A12 chambers described in section 8.2. Chamber measurements were performed inside the calorimeter phantom under the same conditions as were used for the calorimeter measurements except that the water temperature was increased to 22°C. A Delrin chamber holder was attached to the positioning bracket in place of the vessel holder. For the PTW Roos chamber, an additional PMMA support was used to hold the chamber and was inserted into the Derin chamber holder and secured with a nylon screw. For the Exradin A12 chamber, the existing

removable stem pieces were too long to fit in the calorimeter phantom, so these were removed and a shorter Delrin stem was attached to the chamber and inserted into the chamber holder.

For the electron beam measurements, each chamber was positioned in the water so that the effective point of measurement was at d_{ref} . For the PTW Roos chamber, the effective point of measurement is at the inner surface of the top (upstream) electrode and for the Exradin A12 chamber it is 0.5 r_{cav} upstream of the center of the chamber, where r_{cav} is the inner radius of the chamber cavity. For the photon beam measurements only the Exradin A12 chamber was used. In this case the center of the chamber was positioned at the same depth as the thermistors had been positioned in the calorimeter measurements.

The water temperature was measured with a mercury thermometer and the air pressure was measured with a mercury barometer in order to correct for temperature and pressure effects. The mercury thermometer had divisions of 0.1°C and was cross-calibrated versus a NIST-traceable mercury thermometer. Corrections for ion recombination and polarity effects, measured according to the TG-51 protocol⁵, were also applied. In order to correct for any changes in accelerator output, readings were taken before and after both calorimeter and ionization chamber measurements using the NE2571 chamber in a Delrin block inserted into the electron applicator, as described in section 8.2. Air temperature measurements were taken with an alcohol thermometer and these were used along with the pressure measurements to correct for changes in temperature and pressure.

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Chapter 9

The ESW calorimeter: Results and discussion

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9.1 MEAUREMENTS UNDER THE ESW CALORIMETER LID

Figure 9.1 shows the PDD curves measured on the central axis under the calorimeter lid for each beam according to the method described in section 8.4. From the electron beam PDD measurements, R_{50} , the depth at which the dose is

50% of the maximum value, was determined. These values of R_{50} were used to calculate d_{ref} according to equation 2.11 and are listed in Table 9.1



Figure 9.1 PDD curves measured under the calorimeter lid for the photon and electron beams used in this study

Table 9.1 R_{50} and d_{ref} evaluated based on the electron beam PDD measurements in Figure 9.1

Electron beam energy	<i>R</i> ₅₀ (cm)	d _{ref} (cm)
6 MeV	2.25	1.25
9 MeV	3.54	2.02
12 MeV	4.94	2.86
16 MeV	6.64	3.88
20 MeV	8.26	4.86

Profiles were also measured for each beam at several depths and Figure 9.2 shows the profiles across the center of the field at d_{ref} for each electron beam and at 8 cm for the 6 MV photon beam. In the central 7 cm of the field, corresponding to the diameter of the calorimeter vessel, the 6 MV beam is constant within $\pm 1\%$ (Figure 9.2 (a)). The electron beams vary by $\pm 1\%$ over the central 4 cm and then begin to decrease closer to the field edges. The 6 MeV beam displays the narrowest profile, dropping by 8% at 7 cm diameter, while the 20 MeV beam dose decreases by only 3%. Over the central 16 mm region, where the thermistors and ionization chambers measure the dose, all beams are flat within $\pm 0.2\%$ (Figure 9.2 (b)). The asymmetry in the profiles may be caused by variations in the Styrofoam thickness over the field. Looking at the doses at +5 mm and -5 mm (the position of the thermistor probes) these doses differ by at most 0.15% from the dose on the central axis. If the average of +5 mm and -5 mm is taken, the dose agrees with the dose on the central axis within 0.05%. Similarly, the average doses over the central region corresponding to the sensitive volumes of the PTW Roos and Exradin A12 chambers also agree with the central axis dose within 0.05%. Because of this close agreement, no correction for profile non-uniformity was applied, however, an uncertainty of 0.05% was associated with this non-uniformity.



Figure 9.2 Percent dose profiles across the central portion of each beam at d_{ref} for the electron beams (solid lines) and 8 cm for the 6 MV photon beam (dashed line). Points are normalized to 100% at the central axis. For the electron beams in (a), the 6 MeV beam is the narrowest and the beam width increases with energy, so that the 20 MeV beam has the widest profile. (b) focuses on the central 16 mm of the field.

9.2 CALIBRATIONS

9.2.1 Calibration of the PT-100 RTD probes

The PT-100 RTD temperature probes were calibrated according to the method described in section 8.5.2.1. From the analysis of this calibration, the resistance as a function of temperature was determined and a straight line was fit to the data. Table 9.2 shows the slope, intercept and residual of the linear fit for the three probes used. When using the average of all three probes to determine the temperature, the combined uncertainty on the slope is 0.08%.

Table 9.2 Average slope, intercept and residual for the linear fits to the RTD calibration of resistance as a function of temperature over the temperature range -4° C to 12° C. The numbers in parentheses indicate the one standard deviation uncertainty on the final digit.

RTD probe number	Slope (Ω/°C)	Intercept (Ω)	\mathbf{R}^2
1	0.3903 (5)	100.020 (6)	0.99995
3	0.3906 (6)	100.03 (2)	0.99993
4	0.3902 (6)	100.057 (8)	0.99998

9.2.2 Calibration of the thermistor probes

The thermistor probes were calibrated according to the method described in section 8.5.2.2. Using a second order fit to the log of the resistance as a function of temperature, the parameters β and R_0 were calculated. The average β and R_0 values are shown in Table 9.3, along with uncertainties corresponding to one standard deviation. The probes were also calibrated at NRC and the values of β and R_0 agreed within 0.2%. Initially probes 1 and 2 were used, however, probe 1 became damaged and had to be replaced with probe 4. β and R_0 show little variation with temperature over the range we have used in our calorimetry experiments (less than 0.07% between 3.9 and 4.1°C), so these values were treated as constants for our purposes. When combining the statistical uncertainty and the ±0.035% variation over the temperature range with the uncertainty on the

slope of the RTD probes, this results in an overall uncertainty on β of 0.14% to 0.22% and an average uncertainty of 0.19%.

Table 9.3 Average β and R_0 values at 4°C for thermistor probes along with percent uncertainties corresponding to one standard deviation.

Thermistor probe number	β	R_0
1	$3022\pm0.1\%$	$4394\pm0.1\%$
2	$3144\pm0.2\%$	$4434\pm0.1\%$
4	$3105\pm0.2\%$	$4243\pm0.1\%$

9.2.3 Calibration of the AC bridge

As mentioned in section 8.5.2.3, for each set of approximately 10 calorimeter runs, at least two AC bridge calibrations were performed. Figure 9.3 shows a typical bridge calibration for (a) the passive bridge, and (b) the active bridge. Combining all of these calibrations for a given bridge and thermistor pair, we can plot the bridge output voltage change due to the 1 Ω resistance change as a function of water temperature. This is shown in Figure 9.4 for (a) the passive bridge with thermistors 1 and 2, (b) the passive bridge with thermistors 2 and 4 and (c) the active bridge with thermistors 2 and 4. The χ^2 for the data shown was combined with the uncertainty due to the temperature determination (0.02°C) to determine an overall uncertainty in the conversion of ΔV to $\Delta R/R$ of 0.13%.



(b)

Figure 9.3 Examples of bridge calibration measurements for (a) the passive AC bridge and (b) the active AC bridge. Points between the pairs of dashed lines were not included in determining the linear fit.



Figure 9.4 Calibration of the voltage change for a 1 Ω resistance change as a function of water temperature for (a) the passive bridge with thermistors 1 and 2, (b) the passive bridge with thermistors 2 and 4 and (c) the active bridge with thermistors 2 and 4. The total decade box resistance is approximately 20 k Ω , so 1 Ω represents a 0.005% fractional resistance change.

9.3 CORRECTION FACTORS

9.3.1 Corrections for the change in water density, k_{ρ}

As described in section 8.5.3.1, the effect of the change in water density between room temperature and 4°C must be corrected for. The density of water at 22°C is 997.8 kg/m³. This converts to a depth difference of 0.2 mm at 8 cm depth. Based on the PDD measurements in photon beams from section 9.1, for the 6 and 18 MV photon beam measurements at 8 cm the dose is 0.1% lower if the measurement is 0.2 mm deeper. For all of the other depths the difference in density results in an effective difference in depth of 0.1 mm or less. In these cases the density correction is negligible, so no correction was applied. The uncertainty associated with the density correction was estimated to be 0.05%.

9.3.2 Correction for the chemical heat defect, k_{HD}

As described in section 8.5.3.2, we used both hydrogen- and nitrogen-saturated pure water systems in our experiments. As will be elaborated on in section 10.3, no evidence of an unstable heat defect was seen in either system and the two systems showed excellent agreement. Based on this, we have used the value given in Ref.1 of 1.000 ± 0.003 for the heat defect.

9.3.3 Correction for perturbations of the radiation field, $k_{\rm p}$

The values of k_P for each photon and electron beam determined using Monte Carlo simulation as described in section 8.5.3.3 are shown in Table 9.5 and Table 9.6. Figure 9.5 shows the variation in k_P with depth for the 6 and 20 MeV electron beams. The perturbation includes both attenuation, which will decrese the dose resulting in a correction greater than 1, and scatter, which will increase the dose resulting in a correction less than 1. The uncertainty in k_P due to position in the Monte Carlo evaluated corrections was 0.6% for the 6 MeV electron beam and 0.1% or less for all other beams. These uncertainties correspond to a thermistor position uncertainty estimate of 0.4 mm. This uncertainty related to thermistor position was combined with the statistical uncertainties for the simulations (0.1% for photon and 6 MeV electron beams and 0.2% for 9 to 20 MeV electron beams) to determine the overall uncertainty in $k_{\rm P}$. Other validations of this factor will be described in section 10.5.



Figure 9.5 Correction for perturbations to the radiation field due to the glass vessel as a function of depth for the (**a**) 6 MeV and (**b**) 20 MeV electron beams.

9.3.4 Corrections for heat transfer by conduction, $k_{\rm HT}$

The correction for heat transfer by conduction due to the dose gradient and nonwater materials was determined according to the method described in section 8.5.3.4. Table 9.4 lists the material properties used in the finite element analysis program COMSOL MULTIPHYSICS along with the sources for these values. Figure 9.6 shows the resulting thermal distributions after 10 successive irradiations for the (a) 6 and (b) 20 MeV beams. When comparing the amount of conductive heat transfer extrapolated to the mid-irradiation time (the inverse of the heat transfer correction), less than 0.2% difference is seen between runs 1 and 10, as shown in Figure 9.7 for the (a) 6 and (b) 20 MeV beams. Table 9.5 and Table 9.6 show the values of $k_{\rm HT}$ for each beam with different irradiation times, drift times and depths. The uncertainties are based on the agreement between measured and simulated post-irradiation drift curves, as will be explained in section 10.6.1. Section 10.6 also describes other validations of $k_{\rm HT}$.

Table 9.4 Material properties at 4°C used in simulating conductive heat transportwith COMSOL MULTIPHYSICS.

material	ρ (kg m ⁻³)	<i>c</i> (J kg ⁻¹ K ⁻¹)	$k (W m^{-1} K^{-1})$
water	1000 ^a	4205 ^b	0.568 ^c
Pyrex glass	2230 ^d	800 ^e	1.164 ^f
air	1.274 ^a	1006 ^a	0.0244 ^a

a. Taken from Ref. 2.

b. Taken from Ref. 3.

c. Taken from Ref. 4.

d. Taken from Ref. 5.

e. Taken from Ref. 6.

f. Taken from Ref. 7.



(a)



(b)

Figure 9.6 Simulated temperature distributions following 10 successive 40 s irradiations for the **(a)** 6 and **(b)** 20 MeV electron beams.



Figure 9.7 Normalized post-irradiation drifts showing the conductive heat transfer for successive simulated irradiations (runs 1 to 10) for the **(a)** 6 and **(b)** 20 MeV electron beams. The extrapolation to the mid-irradiation time (-20 s) is shown for runs 1 and 10. Note that cooling due to the dose gradient is dominant for 6 MeV, while exces heat from the glass vessel can be observed in the case of 20 MeV.

Beam	k _P	Irradiation time (s)	k _{HT}
6 MeV	1.024(6)	40	1.016 (6)
		20	1.012 (6)
		80	1.023 (6)
9 MeV	0.999(2)	40	1.010 (2)
12 MeV	0.999(3)	40	1.007 (1)
		20	1.005 (1)
16 MeV	1.000(3)	40	1.006 (1)
20 MeV	1.001(3)	40	1.004 (1)
		20	1.003 (1)

Table 9.5 $k_{\rm P}$ and $k_{\rm HT}$ for different electron beams and irradiation times. Numbers in parentheses indicate the uncertainty on the final digit.

Table 9.6 $k_{\rm P}$ and $k_{\rm HT}$ for different photon beams, depths and irradiation and drift times. Numbers in parentheses indicate the uncertainty on the final digit.

Beam	depth (cm)	<i>k</i> _P	t _{pre} (s)	<i>t</i> _{irr} (s)	t _{post} (s)	k _{HT}
6 MV	2	1.002(1)	180	40	180	1.004 (1)
			180	100	180	0.996 (1)
	5	1.004(1)	180	40	180	1.007 (1)
			180	180	180	0.989 (1)
	8	1.004(1)	60	40	90	1.008 (1)
			60	67	90	1.009 (1)
			60	100	90	1.008 (1)
			180	10	180	1.007 (1)
			180	20	180	1.007 (1)
			180	40	180	1.007 (1)
			180	100	180	1.000(1)
			180	180	180	0.989 (1)
18 MV	8	0.999(1)	60	50	90	1.009 (1)
			60	100	90	1.008 (1)
			60	200	90	0.999 (1)
			180	100	180	1.000(1)
⁶⁰ Co	5	1.002(1)	180	180	180	0.989 (1)

9.4 CORRECTION FOR CHANGES IN ACCELERATOR OUTPUT

The correction for the difference in accelerator output over the measurement period was determined using the NE 2571 as a monitor chamber, as described in section 8.7, and ranged from 0.997 to 1.007. The uncertainty on the measurements with the monitor chamber was estimated to be 0.1% for all beams. This was based on the standard deviation of 5 consecutive sets of 5 measurements of a 200 MU irradiation. The block and monitor chamber were removed and re-inserted between each set.



Figure 9.8 Relative difference between 5 consecutive sets of measurements with the NE 2571 monitor chamber taken for the 9 to 20 MeV electron beams. The chamber and block were removed from the applicator and inserted again between each set of measurements. Each set of measurements represents five 200 MU irradiations.

9.5 CALORIMETER MEASUREMENTS

Calorimeter measurements were carried out as described in section 8.6. Examples of calorimeter runs are shown in Figure 9.9 for (a) the passive bridge and (b) the active bridge. The transient behaviour at the beginning and end of the irradiation in (a) is most likely due to leak impedances between thermistor leads and grounding

(or guarding) that change due to the irradiation of wires and insulators. These would show up in the passive bridge configuration whereas they disappear in the active bridge configuration (b) since the measurement point (point A in Figure 8.5) is at zero potential. Incomplete balancing of the capacitive component of the bridge signal may have contributed to the magnitude of this effect. Since the pre- and post-irradiation drift periods are used for determining ΔV and measurements with the active and passive bridge were in good agreement, this transient effect was not considered to have a significant influence on the results.

Measurements were taken on 2 to 11 occasions for each beam. On each of these measurement occasions, sets of between 8 and 36 irradiation runs were measured for a beam at a specific depth and with a particular set of timing parameters. The standard uncertainty on the mean was calculated for each set and these ranged from 0.04 to 0.26% with most sets having an uncertainty of 0.1%. In determining the average measurement for each energy, the sets of measurements were weighted by the inverse of the statistical uncertainty, so that sets with a higher uncertainty were given a lower weighting in the overall average. For the combined uncertainty analysis an average of the uncertainties for the sets at each beam energy is used.

As well as the statistical uncertainty, there is also positioning uncertainty for the calorimeter measurements. As mentioned in section 9.3.3, the uncertainty in position is 0.4 mm (combining the 0.3 mm uncertainty from measuring the thermistor position within the vessel and the 0.2 mm uncertainty from positioning the vessel within the water phantom). These are the Type A or randomly varying uncertainties. The systematic or Type B uncertainties associated with the positioning were negligible compared with the random uncertainties. The effect of this positioning uncertainty on the calorimeter measurements depends on the beam and is 0.4% for the 6 MeV electron beam, 0.2% for the ⁶⁰Co and 6 MV photon and 9 and 20 MeV electron beams and 0.1% or less for the 18 MV photon and 12 and 16 MeV electron beams.



(b)

Figure 9.9 Examples of irradiation measurement runs for electron beams with (a) the passive AC bridge and (b) the active AC bridge. Straight line fits to the preand post-irradiation drift measurement are extrapolated to the mid-irradiation time to determine ΔV .

Measurements taken with different irradiation times for electron beams showed good agreement when the associated values of $k_{\rm HT}$ were applied. For the 6, 12 and 20 MeV beams the agreement between 20 and 40 s irradiations was better than 0.2% while the 40 and 80 s irradiations in the MeV beam agreed within 0.4%. The effect of different irradiation times on the photon beam measurements will be discussed in section 10.1.

9.6 IONIZATION CHAMBER MEASUREMENTS

Measurements were taken with the Exradin A12 (SN 310) and PTW Roos (SN 273) ionization chambers as described in section 8.7. For each beam, the chamber was positioned at a depth corresponding to the depth where the thermistors were positioned. For the PTW Roos plane-parallel chamber, the inner face of the front electrode was positioned at the reference depth in the electron beams. The Exradin A12 was positioned with the center of the cavity 0.5 r_{cav} downstream of d_{ref} for the electron beams. Thus the effective point of measurement was at d_{ref} so that the p_{gr} correction, described in section 2.4.3, was not necessary. For photon beams, the center of the Exradin A12 cavity was positioned at the appropriate depth (2, 5 or 8 cm). The uncertainty on positioning in the water phantom was estimated to be 0.2 mm, so that the position uncertainty contributed 0.1% to the measurement uncertainty for the photon and 9 to 20 MeV electron beams and 0.2% to the 6 MeV electron beam measurement.

The average of 5 ionization chamber measurements was taken for each beam on each measurement occasion and the standard deviation of these measurements was 0.04% or less. Measurements of the polarity and recombination corrections were also done for each beam. P_{pol} values ranged from 0.9996 to 1.0007 for both chambers in all beams with an uncertainty of 0.06%. As expected, P_{ion} values showed more variation with beam type and chamber, with a maximum value of 1.0136 for the Exradin A12 in the 16 MeV electron beam and a minimum value of 1.0003 for the Exradin A12 in the ⁶⁰Co beam. The uncertainty on this correction was also estimated to be 0.06%.
A correction was applied to the chamber measurements for variation in pressure and temperature and this ranged from 0.9935 to 1.0179 with a related uncertainty of 0.03%. This is a result of the uncertainty in reading the temperature of 0.05°C and pressure of 0.2 mmHg.

The Exradin A12 chamber was calibrated at NRC in terms of absorbed dose to water in a ⁶⁰Co beam. This calibration coefficient has an associated uncertainty of 0.44% (Ref. 8). Measurements with both chambers were performed using an electrometer that was calibrated at NRC. The correction to the electrometer reading was less than 0.1%, so no correction was applied, but an uncertainty of 0.05% was associated with the electrometer calibration. Leakage currents were negligible for all measurements.

9.7 EVALUATION OF k_o

The following equation was used to determine k_Q from the calorimeter and ionization chamber measurements:

$$k_{Q} = \frac{c_{\rm w} \left(\frac{\Delta R/R}{\Delta V}\right) \left(\frac{\Delta T}{\Delta R/R}\right) M_{\rm cal} k_{\rho} k_{\rm HD} k_{\rm HT} k_{\rm P}}{N_{D_{\rm w}}^{^{60}{\rm Co}} M_{\rm ion} p_{\rm pol} p_{TP}} \frac{\left(M_{\rm mon}\right)_{\rm ion}}{\left(M_{\rm mon}\right)_{\rm cal}},$$
(9.1)

where $(\Delta R/R)/\Delta V$ is determined from the AC bridge calibration, $\Delta T/(\Delta R/R)$ is determined using the temperature and β values according to equation (8.8), M_{cal} is the raw calorimeter reading in μ V/MU, M_{mon} is the monitor chamber reading and M_{ion} is the uncorrected ionization chamber reading in nC/MU.

9.7.1 Summary of uncertainties

Summaries of the uncertainties relating to establishing the dose for the ESW calorimeter and the ionization chambers are given in Table 9.7 and Table 9.8. In these tables, the uncertainties are listed as Type A or Type B. The Type A uncertainties indicate the random deviation in quantities that are evaluated independently for each set of measurements, i.e., the raw calorimeter and ionization chamber readings, the monitor chamber readings and the depth of the thermistor

probes or ionization chambers. Thus, in combining Type A uncertainties, they are first divided by the square root of the number of independent sets of evaluations for each beam and each chamber (given in Table 9.8). Those uncertainties listed as Type B are considered systematic uncertainties and are not affected by the number of measurement sets. The combined percent uncertainties related to the calorimeter and the ionization chamber as well as the combined percent uncertainties in evaluations of k_Q and $k'_{R_{n_0}}$ are given in Table 9.9.

Table 9.7 Summary of the percent uncertainties which are the same for all beams. Quantities marked with an asterisk (*) are not included in uncertainty determination for the $k'_{R_{50}}$ or k_{ecal} values for electron beams.

Beam-independent uncertainties – Ty	pe A (%)
$M_{ m ion}$	0.04
M _{mon}	0.10
Beam-independent uncertainties – Ty	pe B (%)
${\cal C}_{ m W}$	< 0.01
$(\Delta R/R)/\Delta V$	0.13
Absolute temperature	0.01
eta^*	0.19
profile uniformity	0.05
$k_ ho$	0.05
$k_{ m HD}$ *	0.30
$P_{\rm ion}$	0.06
$P_{ m pol}$	0.06
P_{TP}	0.03
Electrometer calibration*	0.05
$N_{\scriptscriptstyle D_w}^{{}^{_{60}Co}}$ *	0.44

	Type	B (%)	Туре А (%)		%)		
Beam	k _{HT}	<i>k</i> _P	M _{cal}	Depth (chamber)	Depth (thermistors)	N (Roos)	N (A12)
6 MeV	0.58	0.63	0.11	0.21	0.42	5	5
9 MeV	0.16	0.24	0.09	0.08	0.16	4	3
12 MeV	0.10	0.26	0.11	0.02	0.04	7	10
16 MeV	0.14	0.26	0.05	0.06	0.11	3	3
20 MeV	0.13	0.27	0.07	0.08	0.16	4	3
6 MV	0.13	0.13	0.12	0.08	0.15	 	11
18 MV	0.13	0.13	0.11	0.07	0.14		3
⁶⁰ Co	0.13	0.08	0.13	0.10	0.21	, , , , , ,	2

Table 9.8 Beam-dependent percent uncertainties. Values of *N*, the number of independent sets for each beam and each chamber, are also given.

Table 9.9 Combined percent uncertainties related to the calorimeter and ionization chamber as well as combined percent uncertainties in evaluation of k_Q and $k'_{R_{so}}$.

Beam	Calorimeter	Ionization Chamber	k _Q	$k'_{R_{50}}$
6 MeV	0.98	0.46	1.08	0.97
9 MeV	0.53	0.46	0.70	0.50
12 MeV	0.51	0.45	0.69	0.48
16 MeV	0.53	0.46	0.70	0.50
20 MeV	0.53	0.46	0.70	0.50
6 MV	0.47	0.45	0.65	
18 MV	0.48	0.46	0.66	
⁶⁰ Co	0.49	0.46	0.68	

9.7.2 k'_{Rso} for electron beams

The electron beam k_Q values were normalized to the interpolated value for $R_{50} = 7.5$ cm in order to obtain values of $k'_{R_{50}}$ (as defined in section 2.6) for comparison with TG-51. In this case, the results are independent of the thermistor calibration β , the ionization chamber calibration coefficient $N_{D_w}^{{}^{\circ}{}_{co}}$ and the chemical heat defect correction k_{HD} , as all of these are considered to be independent of electron energy over this range. The results are shown in Figure 9.10 and Table 9.10 along with values from the TG-51 protocol. The combined uncertainties associated with these evaluations are 1.0% for 6 MeV and 0.5% for 9 to 20 MeV. The results evaluated with the ESW calorimeter are in agreement with TG-51 values for the 12 to 20 MeV beams, however, for the 9 MeV beam, the calorimeter values are 0.9% and 1.0% higher than the TG-51 values for the Roos and A12 chambers, respectively. For the 6 MeV beam, the calorimeter value is 1.2% higher.

Table 9.10 Values of $k'_{R_{50}}$ for the PTW Roos and Exradin A12 chambers determined using the ESW calorimeter. Numbers in parentheses represent the uncertainty on the last digit. Values from the TG-51 protocol are listed for comparison.

		РТЖ	Roos	Exrad	lin A12
Beam	R ₅₀ (cm)	ESW	TG-51	ESW	TG-51
6 MeV	2.25	1.05 (1)	1.051	1.04 (1)	1.029
9 MeV	3.54	1.042 (5)	1.034	1.026 (5)	1.018
12 MeV	4.94	1.019 (5)	1.020	1.013 (5)	1.009
16 MeV	6.64	1.006 (5)	1.007	1.004 (5)	1.002
20 MeV	8.26	0.995 (5)	0.996	0.997 (5)	0.998



Figure 9.10 (a) $k'_{R_{50}}$ for electron beams as a function of R_{50} for the PTW Roos and Exradin A12 chambers. Symbols indicate values determined with the ESW calorimeter while lines are values given by TG-51. (b) shows the same ESW calorimeter data normalized to the TG-51 data.

9.7.3 Comparing dose measurements in photon beams

When comparing the dose determined in the photon beam using the ESW calorimeter with the dose determined using the Exradin A12 ionization chamber, we obtained an unexpected result. The ratio of the dose from the calorimeter measurements to the ionization chamber dose was 0.9931 ± 0.0065 for 6 MV, 0.9929 ± 0.0066 for 18 MV and 0.9926 ± 0.0068 for ⁶⁰Co, where the uncertainties represent combined Type A and Type B uncertainties. If we combine the ratios for all photon beam measurements together, the result is 0.9930 ± 0.0065 . Given that measurements with other calorimeters obtained a very good agreement between calorimeter dose and ionization chamber dose for this type of chamber⁹, we decided that further investigation of this difference was necessary. These investigations of the calorimeter system are presented in Chapter 10.

9.7.4 Determining *k*_{ecal} for the Exradin A12 chamber

Using equation (2.17) the quantity k_{ecal} can be determined by:

$$k_{ecal} = \frac{D}{Mk'_{R_{50}}N_{D_{w}}^{^{60}Co}}$$
(9.2)

where *M* is the corrected ionization chamber measurement. We used the $N_{D_w}^{{}^{60}Co}$ and $k'_{R_{50}}$ values for the Exradin A12 chamber determined from the measurements with the ESW calorimeter. Again, because ratios of measurements were used, the result is independent of the thermistor calibration, β , the ionization chamber calibration coefficient given by NRC, $N_{D_w}^{{}^{60}Co}$, and the chemical heat defect correction, k_{HD} . The resulting k_{ecal} is 0.915±0.004, which is 1.0% larger than the TG-51 value of 0.906 for this chamber type.

9.8 DISCUSSION OF RESULTS

The results obtained with the ESW calorimeter show agreement with TG-51 values of $k'_{R_{50}}$ for 12 to 20 MeV electron beams for both the Exradin A12 and PTW Roos chambers. There were significant differences, however, between ESW calorimeter and TG-51 values for k_{ecal} for the Exradin A12 chamber and for $k'_{R_{50}}$ for the PTW Roos chamber at 9 MeV and the Exradin A12 chamber at 6 and 9 MeV. Without understanding the reasons for the discrepancies between the ESW calorimeter and ionization chamber results in photon beams, however, it is difficult to interpret whether these results represent true differences in $k'_{R_{50}}$ and k_{ecal} or if they could be the result of some systematic error. The next chapter will look at possible sources of error in more detail.

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Chapter 10

The ESW calorimeter: Validation and uncertainty

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10.1 EXAMINING THE PHOTON BEAM RESULTS

Because of the 0.7% difference between the calorimetry results in photon beams with the ESW calorimeter and ionization chamber measurements which have been validated using other water calorimeter measurements¹, we did further examinations of our results to investigate what factors might have led to this discrepancy.

Initially we examined the dependence of the photon beam results as a function of several different parameters including photon beam energy, irradiation time and

irradiation depth. These results are shown as the full-drift analysis in Figure 10.1 along with the 1 σ uncertainty. We also considered the effect of the length of preand post-irradiation drifts used in determining the temperature change at the midirradiation point. We re-analyzed both the calorimeter and heat transfer simulation data using only the 40 s before irradiation and the period between 20 and 60 s after irradiation. These results are presented in Figure 10.1 as the short-drift analysis. In the figure, the average ratio of the calorimeter/ionization chamber dose is shown as a solid line at 0.993 and the statistical uncertainty of 0.2% is represented by the dashed lines.

From Figure 10.1 (a) it can be seen that there is no significant deviation in the results for the three different photon beams. This indicates that there is no issue of beam quality dependence of either the chamber or calorimeter. When considering the results as a function of irradiation time in Figure 10.1 (b), the only significant deviations are for the 10 s irradiation full-drift analysis and the 20 s irradiation short-drift analysis, and these deviations are in opposite directions. Because of the low calorimeter signal obtained with these very short photon beam irradiations, they have a larger uncertainty than the results for other time intervals. The results for 40 to 200 s irradiations all agree with the average result within uncertainties. This agreement, as well as the good agreement between the long and short drift analysis, indicates that the heat transfer simulations accurately predict the relative heat transfer behaviour for different timings. Figure 10.1 (c) shows the results as a function of depth for different beams and the two different measured drift times used (60 s pre, 90 s post, indicated as "short" in the figure, and 180 s pre, 180 s post). Again there is good agreement in all cases with the average result, indicating that measurement depth was not a factor.



Figure 10.1 Ratio of dose determined by the ESW calorimeter to dose determined with the Exradin A12 chamber analyzed using the full measured drift (full drift analysis) and 40 s pre-irradiation and 20 to 60 s post-irradiation drift (short drift analysis). Error bars indicate the 1 σ uncertainty. Results are compared in terms of (a) beam quality, (b) irradiation time and (c) measurement depth. The solid line indicates the average for all photon beams and the dashed lines show the 1 σ uncertainty on this average value.

10.2 VALIDATION OF THE CALORIMETER SYSTEM

In order to further validate our measurements with the ESW calorimeter, two sets of experiments were performed at the Ionizing Radiation Standards Laboratory of the National Research Council of Canada (NRC). This laboratory maintains the Canadian national dosimetry standards. The absorbed dose standard for photon beams² is a water calorimeter with many similarities to our system, although designed for measurements in photon beams. We performed measurements in the 6 MV photon beam from an Elekta linear accelerator. In the first set of experiments, we used the NRC calorimeter phantom and vessel and measured the temperature change with our electronics and software. This provided a validation of our versions of the measurement and analysis software (H2ORun and H2OView), the AC bridge, lock-in amplifier and decade resistor box. Comparison of the temperature change measured with our components with that measured using the complete NRC system showed agreement within 0.1%. This gave confidence that our process of measuring the voltage signal and converting it to a temperature change was correct.

The second set of experiments reversed the situation. In this case, the ESW vessel with probes was mounted in the NRC calorimeter phantom and all of the other components belonged to the NRC system. The dose in the 6 MeV beam was calculated based on the calorimeter measurements and compared to the dose obtained with a NE2571 ionization chamber. This chamber was previously calibrated in the same radiation beam using the NRC standard calorimeter. Any differences in the dose could then be due only to properties within the calorimeter vessel itself: corrections for perturbation, chemical heat defect, conductive heat transfer, and thermistor calibration. The thermistor calibration was checked at NRC, as described in section 9.2.2. Two experiments were performed: one with hydrogen-saturated water and one with nitrogen-saturated water, to confirm that gas saturation was not a factor. Both of these experiments indicated that the dose measured with the ESW calorimeter was $0.9\pm0.2\%$ lower than that calculated from the ionization chamber measurements.

10.3 VALIDATION OF k_{HD}

The first possible source of discrepancy tested was the heat defect. As discussed in section 7.1.2, the dissolved gases present in the water system can affect this, so measurements were done with two different gas/water systems. As well, helium leak testing was performed on the glass vessel to determine if gas could leak through any of the seals and no leaks were found. As mentioned, no significant differences between nitrogen and hydrogen-saturated water systems were observed. For photon beams, the results with each system agreed within 0.1%.

Figure 10.2 shows the behaviour of the calorimeter system during the initial irradiations for both the nitrogen- and hydrogen-saturated water systems. The initial measurements with the hydrogen system show a sharp decrease in measured temperature rise over the first 5 irradiations, while the nitrogen system shows a small initial increase in response. Following the first 5 irradiations of approximately 6 Gy, a large dose of 100 Gy was delivered while the water was stirred. In the measurements after this, no change in the response of either system with accumulated dose was observed, indicating that an equilibrium state was reached in both systems.



Figure 10.2 Initial calorimeter measurements for hydrogen-saturated (squares) and nitrogen-saturated (circles) water systems. Each measurement is for an irradiation of approximately 6 Gy. Following the first 5 irradiations, a large dose of 100 Gy was delivered while stirring. Results are normalized to the average of the 10 irradiations following this large dose.

10.4 CONFIRMING VESSEL DIMENSIONS AT 4°C

Since the vessel dimensions at 4°C could affect not only the positioning, but also the perturbation and heat transfer corrections, we measured the separation between the front and back face as well as the thermistor position when the vessel was filled and cooled to 4°C. These dimensions agreed with the dimensions at room temperature within 0.1 mm.

10.5 VALIDATION OF $k_{\rm P}$

10.5.1 Perturbation due to the glass vessel

In order to validate the Monte Carlo calculated values of $k_{\rm P}$, we first compared Monte Carlo simulations, based on a fully optimized beam model of the

accelerator, with measurements of the PDD in water with and without the calorimeter lid. An example for 9 MeV is shown in Figure 10.3. The simulated data is in good agreement with the measured data, correctly predicting the shift in the PDD and the increased dose in the build-up region when the lid is added.



Figure 10.3 PDD curves for a 9 MeV electron beam from Monte Carlo simulations with (open circles) and without (filled squares) the calorimeter lid and from measurements with (dashed line) and without (solid line) the calorimeter lid.

We also measured the vessel perturbation directly using a PTW 30013 waterproof cylindrical ionization chamber. When the thermistor probes are removed from the calorimeter vessel, it is possible to insert this chamber through the thermistor probe port so that it is located at the centre of the vessel. Measurements were taken in a water phantom with 5.5 mm thick PMMA walls with the beam oriented horizontally and the SSD to the PMMA surface set to 105.6 cm. The 10×10 cm² electron applicator and cut-out were used for the electron beam measurements, and for photon beams the field size was set to 10×10 cm² at 100 cm SSD. The ionization chamber was positioned with the axis of the cylinder oriented vertically. The center of the sensitive volume was positioned at 8 cm depth for

the photon beams measurement and, for the electron beams, with the effective point of measurement at d_{ref} for the open electron beam, since it was not possible to position the calorimeter lid in the beam for this measurement set-up. The calorimeter vessel was lowered over the ionization chamber and then raised again.

The dose at the reference depth (d_{ref}) without the calorimeter lid for each beam with and without the glass vessel was measured for the 12 to 20 MeV electron beams and the 6 MV photon beam in order to determine $k_{\rm P}$. These results are shown in Table 10.1. The uncertainty indicated for the measured values corresponds to one standard deviation in the measurements. The measured and Monte Carlo calculated values agree within uncertainties, although the measured values for electron beams are consistently smaller than the Monte Carlo values (0.3 to 0.5%). It should be noted, however, that these measurements were not done under the same conditions as either the Monte Carlo corrections or the actual case for the calorimeter measurements, since it was not possible to place the calorimeter lid in the beam for these measurements. The lid has a negligible effect on the PDD for the 6 MV photon beam, but does alter the dose in the buildup region for electron beams. We ran separate Monte Carlo simulations for 12 to 20 MeV electron beams under the conditions used in the measurement (no lid and 5.5 mm PMMA). These showed excellent agreement with measured results (see Table 10.1), indicating that the Monte Carlo simulations are reliable.

For further comparison, we considered the effect on the dose at d_{ref} of shifting the PDD under the lid by the effective added water thickness due to the front face of the glass vessel, based on the glass density. This was calculated to be 1.4 mm. As can be seen in Table 10.1, the value of k_P for 6 MeV appears consistent with a 1.4 mm shift in the PDD, suggesting that attenuation by the front face of the glass vessel is the major source of perturbation for this beam. The values of k_P for other beams, both from measurements and from Monte Carlo simulations, are smaller than those indicated by a simple shift of the PDD, indicating that scatter from the glass becomes significant for these beams.

Table 10.1 Comparison of Monte Carlo calculated values of k_P with measured values and values calculated by shifting the PDD by 1.4 mm. Uncertainties in the final digit for the Monte Carlo and measured values are indicated by the number in parentheses.

Beam	k _p (Monte Carlo)	k _p (measured in vessel)	k _p (Monte Carlo, no lid)	k _p (calculated from 1.4 mm shift)
6 MeV electrons	1.024 (6)			1.023
9 MeV electrons	0.999 (2)			1.006
12 MeV electrons	0.999 (3)	0.996 (6)	0.995 (3)	1.006
16 MeV electrons	1.000 (3)	0.995 (4)	0.997 (3)	1.006
20 MeV electrons	1.001 (3)	0.997 (2)	0.997 (3)	1.005
6 MV photons	1.004 (1)	1.003 (2)		1.007
18 MV photons	0.999 (1)			1.006
⁶⁰ Co photons	1.002 (1)			1.009

10.5.2 Perturbation due to the vessel holder

We performed ionization chamber measurements in a water phantom both with and without the vessel holder in place to determine whether this could be a significant source of perturbation. The vessel holder produced no observable effect on the ionization chamber reading for the 6 MV photon beam.

10.6 VALIDATION OF $k_{\rm HT}$

Many different parameters were considered that could affect the simulated heat transfer correction. These were evaluated in most cases for the 6 MV beam with 100 s irradiations and with 180 s pre- and post-irradiation drifts. Parameters which produced a change of less than 0.1% on the correction in this case were considered to have a negligible influence on the calorimeter dose.

10.6.1 Comparing simulated and measured post-irradiation drifts

The first step in validating the values of $k_{\rm HT}$ was to compare the measured and simulated post-irradiation drifts. These comparisons are shown in Figure 10.4 for

the 6 MV photon beam and Figure 10.5 for the electron beams. The photon beam drifts were compared for three different irradiation times, 40, 100 and 180 s. The post-irradiation drifts were corrected for the slope of the pre-irradiation drift and normalized to unity 20 s after the end of the irradiation. Each curve represents the average of 10 consecutive irradiations. The differences in the slope of the post-irradiation drift for these different irradiation times can be seen in the figure and the simulated and measured drifts are in good agreement. If a linear fit is extrapolated to the mid-irradiation time, the largest difference between the measured and simulated values is 0.3%.



Figure 10.4 Normalized post-irradiation temperature drift curves for the 6 MeV beam for 40, 100 and 180 s irradiation times. The thin lines correspond to measured drifts and the thick lines to simulated drifts. Each line represents the average of the drifts from 10 consecutive irradiations, corrected for the slope of the pre-irradiation drift. Curves are normalized to unity 20 s after the end of the irradiation.

From the same type of analysis for the electron beam drifts following 40 s irradiations, shown in Figure 10.5, there is good agreement between measured and simulated drifts for the 9 to 20 MeV beams. The largest difference in the extrapolation to the mid-irradiation time is 0.3%. For the 6 MeV beam, the difference between measured and simulated drifts is significant. The values at the

extrapolation time differ by 1.2%. Half of the maximum difference in extrapolated drifts was used as the uncertainty on k_{HT} (see Table 9.5).



(b)

(a)

Figure 10.5 Normalized post-irradiation temperature drift curves for 40 s irradiations from the electron beams. Solid lines correspond to measured drifts and dashed lines to simulated drifts. Each line represents the average of the drifts from 10 consecutive irradiations, corrected for the slope of the pre-irradiation drift. Curves are normalized to unity 20 s after the end of the irradiation. Measurements with the passive and active AC bridges are shown in **(a)** and **(b)** respectively.

10.6.2 Comparing finite element analysis software

We performed validations of k_{HT} determined using COMSOL MULTIPHYSICS by comparing it to two other codes for finite element analysis: FlexPDE and an in-house code. Since these codes apply to cylindrically symmetric geometries, two different cases were compared:

- a cylindrically symmetric vessel and probes based on the NRC calorimeter vessel²
- 2. separate cylindrically symmetric calculations of the vessel and the probes of the ESW calorimeter vessel which were summed

These comparisons were made for a simulated uniform irradiation, which approximates the conditions for photon beams since the dose gradient in photon beams is small. The agreement between the three codes was within 0.1% for each of the cases studied.

10.6.3 Effect of vessel wall thickness

We examined the effect on k_{HT} for 6 MV if the thickness of the front and rear glass walls was increased from 1.1 mm to 1.2 mm. The change in k_{HT} was negligible.

10.6.4 Effect of vessel ports

To determine whether the ports on the glass vessel (which were not simulated in the original 3D model) affected $k_{\rm HT}$, a second 3D model was created of the vessel alone, without the thermistor probes. In this model the filling and thermistor ports were included. The thermal response was studied first with the vessel port materials set to Pyrex glass and then with these portions set to water, but the main walls of the vessel remaining glass. Avoiding any changes in the geometry prevented any discrepancies due to the automatic meshing procedure used by COMSOL MULTIPHYSICS. The effects were studied for a 6 MV beam using the corresponding PDD for a flat field. The square field size was set to $16 \times 16 \text{ cm}^2$. The reason for increasing the field size was to match the portion of the vessel ports in the irradiation field during experiments. The field size corresponds to the length along the diagonal at 8 cm depth, since the ports are

oriented along the diagonals of the field during experiments. No significant effect of the glass vessel ports on $k_{\rm HT}$ at the position of the thermistor probes was observed.

10.6.5 Effect of field size

In order to determine whether changing the field size has any effect on k_{HT} , we examined the value of the conductive heat transport correction factor for three different field sizes: 10×10, 15×15 and 20×20 cm². Field size had no significant effect on k_{HT} .

10.6.6 Effect of excess heat outside glass vessel

We performed measurements with the thermistor probes directly in the water phantom to determine the amount of excess heat during irradiation due to impurities in the water outside the vessel. These measurements showed that the heating of the water outside the vessel was 3% more than inside the vessel. This was similar to early open calorimeter results using once distilled water. Including this excess heat in the heat transfer simulations, however, produced no noticeable effect on the correction factors.

10.6.7 Effect of dose at glass interfaces

We did a closer examination of the dose at the glass interfaces for the 6 MV photon beam using Monte Carlo simulation. The 2 mm behind the front face of the vessel and in front of the rear face were divided into 0.2 mm segments. Looking at the perturbation factor (dose without glass vessel / dose with glass vessel) shown in Figure 10.6, the dose immediately behind the glass is reduced by 1.4% due to attenuation but quickly increased and 2 mm behind the glass it is only 0.6% lower. 2 mm in front of the rear glass face the dose is 0.3% higher than the dose without the vessel and quickly increases to 6.1% higher immediately in front of the glass.

The doses at these interfaces within the calorimeter vessel were included in the COMSOL MULTIPHYSICS heat transfer model. The effects outside the vessel were not included. Including these effects changed the heat transfer correction for 100 s irradiation with 6 MV photons by less than 0.03%. Even if the effects outside the vessel were included, the influence on $k_{\rm HT}$ would be less than 0.1%.



Figure 10.6 Vessel perturbation effect for a 6 MV photon beam, focusing on the 2 mm immediately behind the front glass face and immediately in front of the rear glass face.

10.6.8 Effect of thermistor position

Changing the relative position of the thermistor relative to the front wall of the vessel had a small effect on $k_{\rm HT}$ for the 6 MV photon beam. A 1 mm change in thermistor position changed $k_{\rm HT}$ by 0.1%. Since our position uncertainty is smaller than 1 mm, this effect was not considered to significantly influence the photon beam results.

10.6.9 Effect of run number

The thermal response was modeled by COMSOL MULTIPHYSICS over a period of 10 simulated irradiations and associated drifts. Examining each run showed that, although the relative slope of the post-irradiation drift changed, the extrapolation at the mid-irradiation time, on which $k_{\rm HT}$ is based, remained constant within 0.2% for all beams.

10.6.10 Efffects of material parameters

The validity of the reference data as well as the effects on k_{HT} of altering the material parameters were examined for Pyrex and water. For water, since the specific heat capacity and density are included in determining the dose both in the presence and absence of conduction, these parameters were not considered to affect k_{HT} . The air layer above the water does not affect heat transport at the depths used for photon beam measurements, so air parameters were not considered.

10.6.10.1 Pyrex glass density

The density of the glass used for the front and back faces of the ESW vessel was measured and found to be 2.2 g/cm³, which is in agreement with the density of Pyrex glass from the NIST database³ of 2.2 g/cm³. Nevertheless, we examined changing the density of the glass in the COMSOL MULTIPHYSICS model. Using a density of 2.4 g/cm³, a difference of 8%, the effect on $k_{\rm HT}$ was less than 0.1%.

10.6.10.2 Pyrex glass specific heat capacity

Considerable difference in specific heat capacity values for Pyrex glass was found in the literature. Values reported ranged from 750 to 840 J·kg⁻¹·K⁻¹, a 12% variation. This may be due to values being reported for different temperatures, however, for many references the temperature was not listed. The value of 800 J·kg⁻¹·K⁻¹ used in our model was taken from Ref. 4 and corresponds to the result at 4°C. According to these results, it is possible that the values reported elsewhere correspond to temperatures ranging from approximately -20°C to 20°C. Changing the value of c_{glass} to 840 J·kg⁻¹·K⁻¹ (a 5% increase) had a negligible effect on k_{HT} .

10.6.10.3 Pyrex glass thermal conductivity

In looking at the literature for thermal conductivity of Pyrex glass, it appears that the value of 1.164 W m⁻¹ K⁻¹ given in Ref. 5 may actually be at room temperature. The value at 4°C given in Ref. 6 is 1.111 W m⁻¹ K⁻¹, a difference of 5%. Changing this parameter, however, produced no noticeable effect on $k_{\rm HT}$.

10.6.10.4 Water thermal conductivity

We examined the effect on $k_{\rm HT}$ of changing the water thermal conductivity from a value of 0.568 W m⁻¹ K⁻¹, the value at 4°C, to 0.602 W m⁻¹ K⁻¹, the value at 22°C, a difference of 6%. This did have a significant effect on $k_{\rm HT}$, reducing it by 0.3% for the 6 MV, 100 s irradiation case. Based on this, however, the value of the conductivity would have to be significantly lower than the reference value for 4°C in order to improve the agreement between calorimeter and ionization chamber doses.

10.7 FINDINGS OF VALIDATION TESTS

A summary of the results of the validation tests is given in Table 10.2. The largest effect was produced by varying the water thermal conductivity. From these results, no obvious sources were found for the difference between the ESW calorimeter measurements and measurements based on the NRC calorimeter in photon beams. We would not expect all of these effects to produce changes to the photon beam result in the same direction, however there always remains the possibility that the difference observed is the result of several small effects that individually could be considered insignificant. Further investigations will need to be performed to resolve this discrepancy. From the values in Table 10.2, only the uncertainties in $k_{\rm HT}$ from comparing the measured and simulated post-irradiation temperature drifts were used in the uncertainty analysis given in section 9.7.1. The other effects were not determined with sufficient precision to be included in the uncertainty estimate.

	Parameter tested	Effect on 6 MV photon beam result
$k_{ m HD}$	hydrogen-saturated versus nitrogen-saturated water systems	< 0.1%
kр	Monte Carlo versus measured factors for the glass vessel	≤ 0.1%
	perturbation due to the vessel holder	< 0.1%
k _{HT}	measured versus simulated post-irradiation drifts	≤ 0.3%
	different finite element analysis software	< 0.1%
	vessel wall thickness	< 0.1%
	vessel ports	< 0.1%
	field size	< 0.1%
	3% excess heat outside vessel	< 0.1%
	dose at glass interfaces	< 0.1%
	thermistor position	$\leq 0.1\%$
	run number	$\leq 0.2\%$
	Pyrex glass density	< 0.1%
	Pyrex glass specific heat capacity	< 0.1%
	Pyrex glass thermal conductivity	< 0.1%
	Water thermal conductivity	$\leq 0.3\%$

 Table 10.2
 Summary of validation test results for the 6 MV photon beam.

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Chapter 11

The ESW calorimeter: Conclusions and future work

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11.1 CONCLUSIONS

In this project, we constructed a sealed water calorimeter, specifically designed for measurements in clinical electron beams. We were able to perform reproducible measurements in a clinical linear accelerator for electron beams with energies as low as 6 MeV. This is an important finding, as, previously measurements in low-energy electron beams were considered unfeasible due to the temperature drifts produced by the high dose gradients.

We were able to account for the effect of perturbations to the radiation field caused by the glass calorimeter vessel using Monte Carlo simulations for both electron and photon beams. These simulated results were verified by direct measurements in the calorimeter vessel for the 12 to 20 MeV electron and 6 MV photon beams. For the 6 MeV electron beam, the validity of the correction was inferred by noting the close agreement found by shifting the PDD by the effective change in depth caused by introducing the glass front face of the vessel. Since scatter from the other glass surfaces would be expected to have a negligible effect at the measurement point within the vessel for this low-energy beam, this method of verification was considered reasonable for this case.

Using the finite element modeling software COMSOL MULTIPHYSICS, we were able to model the conductive heat transport present in both electron and photon beam measurements. Using the technique of extrapolation of the pre and post-irradiation drifts to the mid-irradiation point, we were able to demonstrate consistent results for 20 and 40 s irradiations with 6, 12 and 20 MeV electron beams and for 40 to 200 s photon beam irradiations. Examination of the measured and simulated post-irradiation drifts showed very good agreement for 9 to 20 MeV electron beams and 6 MV photon beams. The largest resulting discrepancy on the extrapolation to the mid-irradiation point was 0.3% for the sets examined at these energies. A noticeably larger deviation was noticed for the 6 MeV electron beam, with a 0.6% deviation between measured and simulated extrapolations at the mid-irradiation point.

Due to the very steep gradient of the 6 MeV beam, there are large position-related uncertainties associated with the results for this energy. These are affected not only by the depth of the thermistors within the phantom, but also, for the vessel perturbation effect, by the position of the thermistors relative to the front face of the glass vessel. These effects along with the uncertainties in modeling the conductive heat transport for this beam significantly increase the uncertainty associated with the 6 MeV calorimeter measurements, producing a combined uncertainty of 0.97%. The broader maximum dose region for the higher energy electron beams made measurements at these energies much less dependent on position, so the uncertainties for these energies are between 0.51 and 0.53%. Uncertainties on calorimeter measurements for photon beams are between 0.47 and 0.49%. These are only slightly larger than the reported uncertainty on the NRC calorimeter, the dominant components of the uncertainty are the chemical heat defect correction (0.3%) and the thermistor calibrations (0.19%).

The photon beam dose determined from measurements with the ESW calorimeter was consistently 0.70% lower than the dose determined using the Exradin A12 ionization chamber, which was outside the combined uncertainty on the dose ratio of 0.65%. This was surprising since this ionization chamber had been calibrated in ⁶⁰Co based on the NRC water calorimetry standard and previous measurements showed good agreement between water calorimeter dose and ionization chamber dose for this chamber type in megavoltage photon beams². Further investigations showed differences of 0.9±0.2% between measurements with the ESW calorimeter vessel and measurements with the NRC standard calorimeter vessel. This pointed to some type of systematic difference related to the corrections used for water calorimeter measurements with this vessel. Several investigations were performed to examine the correction factors in more detail, however the source of the discrepancy was not entirely discovered.

Using the ESW calorimeter measurements, we determined values of $k'_{R_{50}}$ for the 6 to 20 MeV electron beams. Since $k'_{R_{50}}$ is calculated by normalizing the electron beam absorbed dose beam quality conversion factors to the value at $R_{50} = 7.5$ cm, the values of $k'_{R_{50}}$ are independent of the chemical heat defect correction and thermistor calibrations, which are considered to be constant over the range of electron beam energies used. As well, they do not depend on the ionization chamber absorbed dose calibration coefficient. The uncertainties for our values of $k'_{R_{50}}$ were 0.48 to 0.50% for the 9 to 20 MeV electron beams and 0.97% for the 6 MeV electron beam. Comparing the values determined using the ESW calorimeter with values in the TG-51 protocol showed good agreement for the 12 to 20 MeV beams for both the Exradin A12 and PTW Roos ionization chambers. For the 9 MeV beam, the ESW calorimeter values were 0.9 and 1% larger for the Roos and A12 chambers, respectively. The ESW calorimeter and TG-51 values of $k'_{R_{50}}$ for the PTW Roos chamber agreed within uncertainties for the 6 MeV electron

beam, however for the Exradin A12 chamber, the ESW calorimeter value was 1.2% higher at this energy.

From the photon and electron beam measurements with the ESW calorimeter the value of k_{ecal} for the Exradin A12 chamber was determined to be 0.915±0.04, 1.0% higher than the value given in TG-51 of 0.906.

Because of the unresolved discrepancy for the photon beam dose measurements with the ESW calorimeter, it remains unclear whether the differences noted here are true differences or the result of some systematic error in the determinations with the ESW calorimeter. Depending on the source of the discrepancy, the effects on the dose determination may depend on the beam energy as well as the measurement conditions (e.g. irradiation time), so that even relative dose determinations could be affected. Once this discrepancy is resolved, the factors for electron beams would need to be re-evaluated.

Based on our results, water calorimetry for electron beams with energies between 9 and 20 MeV can be performed with a level of uncertainty similar to that of photon beam water calorimetry. It is also possible to perform reproducible calorimeter measurements for a 6 MeV electron beam, however, uncertainties on calorimeter measurements at this energy become significantly larger due to the steep dose gradient.

11.2 FUTURE WORK

Continued investigation of water calorimetry measurements in electron beams based on this work can proceed in several key areas.

1. Resolving the discrepancy between measurements with the ESW calorimeter and other water calorimetry measurements in photon beams. It is vital that the source of this difference is discovered. Our investigations eliminated several possible sources, but the difference remains. The most likely source of

difference remains the conductive heat transport correction. More extensive comparisons between different finite element analysis codes in modeling this effect are currently underway. It may also be necessary to test other vessel geometries to confirm the validity of these corrections. Whatever modifications are made to the conductive heat transfer model, it must be ensured that the extrapolated results for different irradiation and drift times and different depths remain consistent.

2. Using the ESW calorimeter measurements to determine values of $k'_{R_{s_0}}$ and

 k_{ecal} for different ionization chamber types. Once the issue related to the photon beam discrepancy is resolved, the absorbed-dose beam quality conversion factors for the two chambers studied in this work can be re-evaluated. It is important to also be able to provide calorimeter-based factors for various other chamber types. These could be used in determining the factors provided in future reference dosimetry protocols for electron beams. It would also be useful to study the consistency of these factors for several chambers of the same type to determine if certain chamber types are more suitable for reference dosimetry measurements in electron beams.

3. Investigating improvements that will reduce uncertainties associated with low-energy electron beam measurements and allow for measurements at lower electron beam energies. The ESW calorimeter uncertainties for electron beams at energies of 9 MeV and greater are not significantly larger than uncertainties for photon beam measurements with other sealed water calorimeter systems. However, the uncertainty for measurements in a 6 MeV beam becomes significantly larger and measurements at d_{ref} for electron beams with energies lower than 6 MeV are not possible with the current ESW calorimeter design. In order to reduce the uncertainty, first of all, the method of determining the thermistor depth, both in relation to the front face of the vessel and within the calorimeter phantom, must be improved, as this positioning uncertainty has a major effect on the dose determination for low-energy electron beams. It would also be advantageous to construct a calorimeter vessel with a thinner front glass face and with a smaller separation between the front face and the thermistor probes. A thinner front glass

face would produce less perturbation of the radiation field for low-energy beams and, if the thermistors are closer to the front face, they could be positioned at $d_{\rm ref}$ for lower energy electron beams, for example 4 MeV ($d_{\rm ref} \cong 0.8$ cm). Finally, further validation of the conductive heat transfer models would need to be performed for these low-energy beams. In particular, the reason for the discrepancy between measured and simulated post-irradiation temperature drifts must be determined and corrected.

4. Developing a water calorimeter standard for electron beams. Based on the results of this work, it appears feasible to construct an absorbed dose standard based on water calorimetry for electron beams with energies between 9 and 20 MeV. Ionization chambers could then be directly calibrated at several electron beam energies.

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Chapter 12

General conclusions

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12.1 FULFILLMENT OF OBJECTIVES

Through the work presented in this thesis, we were able to fulfill our two main objectives.

1. We developed and tested prototype models of a guarded liquid ionization chamber. We were able to determine an appropriate design and materials so that the GLIC-03 chamber achieved reasonable stability for measurements over several hours. Using the GLIC-03, we were able to study general ion recombination behaviour as a function of applied electric field and dose per pulse in pulsed megavoltage photon beams from a clinical linear accelerator. We tested a theoretical method to correct for general recombination which was based on the theory for ion recombination in gases. We also developed an empirical method which could be used to provide a relative correction for general recombination in cases where the theoretical method was not applicable. The agreement between the two methods was within 0.6%.

We tested the energy dependence of the GLIC-03 in 6 and 18 MV photon beams and found that filling the chamber with liquid reduced its energy dependence by 1% between these two energies. We compared PDD measurements in the build-up region of an 18 MV photon beam taken with the GLIC-03 chamber with measurements taken using other detectors. Using the empirical general recombination corrections, results with the liquid-filled GLIC-03 showed excellent agreement with measurements taken with an extrapolation chamber, indicating that this method of recombination correction is valid. As well, since the extrapolation chamber is known to produce negligible perturbation of the irradiation field, this agreement indicated that there is no significant perturbation produced by the GLIC-03.

2. We developed an electron sealed water (ESW) calorimeter, specifically designed for measurements in clinical electron beams. We were able to use this device to perform reproducible measurements in 6 to 20 MeV electron beams from a clinical linear accelerator. We also performed measurements in a ⁶⁰Co beam and in 6 and 18 MV photon beams. Using EGSnrc Monte Carlo simulations, we were able to provide correction factors for the perturbation of the radiation field caused by the glass calorimeter vessel. Measurements showed excellent agreement with these simulations. We used finite element analysis software to simulate the conductive heat transport for each electron and photon beam. There was good agreement between measured and simulated post-irradiation drifts for the 9 to 20 MeV electron and 6 MV photon beams. The overall uncertainty associated with the ESW calorimeter dose for 9 to 20 MeV electron beams was 0.5%, which compares favorably with the 0.4% uncertainty reported for calorimeter measurements in photon beams. The uncertainty associated with the 6 MeV measurements is significantly larger, 1.0%, and is primarily due to the effects of positioning uncertainties, since the dose gradient is very steep at this energy.

We compared results using the ESW calorimeter with the water calorimetry standard at NRC for a 6 MV photon beam. The difference between the two

calorimeter systems was $0.9\pm0.2\%$. We suspected some type of systematic error was responsible for this difference and the potential source of this error was isolated to factors relating to the calorimeter vessel itself. Several tests were done to validate the chemical heat defect, glass perturbation and conductive heat transport correction factors. No significant source of error was found, so the reason for the discrepancy between the calorimeter systems remains unclear. The most likely cause, by the exclusion of other causes, remains issues with heat transport near the vessel components.

Assuming that the systematic difference between the ESW calorimeter and the national primary standard is, within overall uncertainties, energy independent, beam quality conversion factors for 2 commercial chambers, the Exradin A12 and the PTW Roos, were measured using the ESW calorimeter in 6 to 20 MeV electron beams. These values were compared with values reported in the TG-51 protocol and differences of up to 1.2% were found.

12.2 RESOLUTION OF HYPOTHESES

1. A guarded liquid ionization chamber (GLIC) will provide high-resolution energy-independent and perturbation-free dose information for relative dosimetry.

The GLIC-03 liquid ionization chamber which we developed has very high spatial resolution, with a sensitive volume that is approximately 2 mm³. We found that the energy dependence of the liquid-filled GLIC-03 chamber between 6 and 18 MV photon beams was 1% less than that of the same chamber filled with air. Further comparisons of the GLIC-03 with an extrapolation chamber in measurements in the build-up region of an 18 MV photon beam showed that the perturbation caused by the liquid ionization chamber is negligible. Although the current lack of long-term stability with this chamber makes it an inconvenient device for clinical measurements, we expect that these stability issues will be resolved in future chamber designs so that liquid ionization chambers can become useful devices for improving the accuracy of relative dose measurements in the clinic.

2. Accurate absolute dosimetry for clinical electron beams can be performed using an electron sealed water (ESW) calorimeter.

With the ESW calorimeter, we showed that reproducible measurements could be performed in electron beams with energies as low as 6 MeV. Through our investigations, we also showed that it is possible to simulate the effects of the dose gradient in electron beams on conductive heat transport during calorimeter measurements. We found that overall uncertainties for 9 to 20 MeV electron beam calorimeter measurements were not substantially larger than uncertainties for calorimeter measurements in photon beams, indicating that the development of a water calorimetry-based standard for electron beams is feasible. Although we currently have a discrepancy between measurements with the ESW calorimeter vessel and the NRC photon standard calorimeter vessel in a 6 MV photon beam, we expect that the source of this discrepancy will be determined. The results from this work can then be re-evaluated in order to provide measured absorbed-dose beam quality conversion factors for the Exradin A12 and PTW Roos ionization chambers in electron beams. This work can be extended to include other types of ionization chambers. By using these measured factors rather than the currently used factors based on calculations, the accuracy of electron beam reference dosimetry will be improved.

For both of these new dosimetry systems, we were able to suggest a number of possible directions for future work based on our experiences. It is hoped that progress will continue in developing each of these areas so that they can become fully implemented in the clinical dosimetry process and that, through their application, these devices will improve the accuracy of dose determination for radiation therapy.
Appendix I

List of commonly used abbreviations

- $%dd(10)_x$ PDD at 10 cm depth for photon beams without electron contamination. Beam quality specifier for photon beams in TG-51 (see section 2.5.1.1).
- CPE Charged Particle Equilibrium (see section 2.2.1)
- D absorbed dose (see section 2.1.1)
- d_{max} depth of maximum dose (see section 2.2.1)
- d_{ref} reference depth for electron beam measurements (see section 2.2.2)
- ESW Electron Sealed Water name given to the calorimeter developed for this thesis
- f ion collection efficiency (see section 3.3.3)
- GLIC Guarded Liquid Ionization Chamber name given to the liquid ionization chambers developed for this thesis
- IAEA -- International Atomic Energy Association, Vienna, Austria

- IMRT Intensity Modulated Radiation Therapy radiation therapy treatment where the radiation intensity is varied across the delivered field.
- k_{ecal} absorbed dose conversion factor from ⁶⁰Co to an electron beam with R_{50} =7.5 cm
- $k_{\rm HD}$ correction for chemical heat defect (see section 7.1.2)
- $k_{\rm HT}$ correction for conductive heat transfer (see section 8.5.3.4)
- $k_{\rm P}$ correction for perturbation of the radiation field caused by non-water materials (see section 8.5.3.3)
- k_O absorbed dose beam quality conversion factor (see section 2.6)
- k_{ρ} water density correction factor (see section 8.5.3.1)
- $k'_{R_{50}}$ absorbed dose conversion factor for electron beams from an electron beam with R₅₀=7.5 cm to another electron beam
- LET Linear Energy Transfer energy transfer per unit path length of an ionizing particle
- MU Monitor Unit Accelerator output based on the readings of the monitor chamber in clinical linear accelerators. 1 MU is set to be approximately equal to 1 cGy at the depth of maximum dose.
- $N_{\rm D}$ absorbed dose calibration coefficient (see section 2.5)
- NIST National Institutes of Standards and Technology, U.S.A.
- NRC National Research Council, Ottawa, Canada
- PDD Percent Depth Dose (see section 2.2)

- $p_{\rm fl}$ fluence perturbation correction factor (see section 2.4.2)
- p_{ion} ion recombination correction factor (see section 2.3.1.3)
- PMMA PolyMethyl MethAcrylate a type of transparent hard plastic
- p_{pol} polarity correction factor (see section 2.3.1.2)
- $p_{\rm TP}$ pressure and temperature correction factor (see section 2.3.1.1)
- p_{wall} wall correction factor (see section 2.4.1)
- R_{50} depth where dose reduces to 50 % of maximum value in electron beams (see section 2.2.2)
- RTD Resistance Temperature Detector
- s restricted mass collision stopping power for electrons (see section 2.4)
- SAD Source Axis Distance (see section 2.5.1.1)
- SSD Source Surface Distance (see section 2.5.1.1)
- TCPE Transient Charged Particle Equilibrium (see section 2.2.1)
- TPR Tissue Phantom Ratio (see section 2.5.1.1)
- β parameter used in describing the change in thermistor resistance with temperature (see section 8.5.2.2)

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