TRANSIT DOSIMETRY IN ^{192}Ir HIGH DOSE RATE BRACHYTHERAPY

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the Degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

28th day of October 2009

ABSTRACT

Background and purpose: Historically HDR brachytherapy treatment planning systems ignore the transit dose in the computation of patient dose. However, the total radiation dose delivered during each treatment cycle is equal to the sum of the static dose and the transit dose and every HDR application therefore results in two radiation doses. Consequently, the absorbed dose to the target volume is more than the prescribed dose as computed during treatment planning. The aim of this study was to determine the magnitude of the transit dose component of two ^{192}Ir HDR brachytherapy units and assess its dosimetric significance.

Materials and Methods: Ionization chamber dosimetry systems (well-type and Farmer-type ionization chambers) were used to measure the charge generated during the transit of the ^{192}Ir source from a GammaMed and a Nucletron MicroSelectron HDR afterloader using single catheters of lengths 120 cm. Different source configurations were used for the measurements of integrated charge. Two analysis techniques were used for transit time determination: the multiple exposure technique and the graphical solution of zero exposure. The transit time was measured for the total transit of the radioactive source into (entry) and out of (exit) the catheters.

Results: A maximum source transit time of 1.7 s was measured. The transit dose depends on the source activity, source configuration, number of treatment fractions, prescription dose and the type of remote afterloader used. It does not depend on the measurement technique, measurement distance or the analysis technique used for transit time determination.

Conclusion: A finite transit time increases the radiation dose beyond that due to the programmed source dwell time alone. The significance of the transit dose would increase with a decrease in source dwell time or a higher activity source.

Keywords: transit time/dose, HDR brachytherapy, HDR planning system, afterloader, ionization chamber dosimetry system, source configuration, multiple exposure technique.

DEDICATION

In loving memory of my father

Tumasang Michael Tabufor

1930 – 2003

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AAPM: The American Association of Physicists in Medicine.

C: Coulomb, the SI unit of charge. Subunit is nanocoulomb (nC).

Ci: Curie, the old unit of activity. The SI unit is the Becquerel (Bq). 1 Ci = $3.7 * 10^{10}$ Bq.

cm: Centimetre.

CMJAH: Charlotte Maxeke Johannesburg Academic Hospital.

$\mathbf{d_{ref}}$: Reference distance of 1 m.

$\mathbf{\check{D}_R(r)}$: Dose rate at point R from a point source, where r is the radial distance from the source position (at the centre) to point R.

EPR: Electron paramagnetic resonance.

ESTRO: European Society for Therapeutic Radiology and Oncology

Gy: Gray, the unit of absorbed dose.

HDR: High dose rate.

h: Hour.

I: Current.

IAEA: International Atomic Energy Agency

^{192}**Ir:** Iridium-192 radionuclide.

$\mathbf{K_R}$: Reference air kerma rate. Term used to specify the strength of brachy-therapy photon emitting sources such as ^{192}Ir. Unit is $\mathbf{\mu Gys^{-1}}$ or $\mathbf{mGyh^{-1}}$.

LDR: Low dose rate.

m: Metre, the SI unit of distance measure. Subunits are mm and cm. m is also used in this report to represent the number of source transfers.

M: Charge reading.

min: Minute.

MDR: Medium dose rate.

NCS: Netherlands Commission on Radiation Dosimetry.

PTW: Physikalisch Technische Werkstätten

QA: Quality assurance.

s: Second, the SI unit of time.

SCD (or **SDD):** Source-to-chamber distance (or source-to-detector distance).

S_k: Air kerma strength. As recommended by the AAPM TG 43[14], it is a term used to specify the strength of a brachytherapy photon emitting source. Unit is ***cGy.cm^{2}h^{-1}***. A shorthand notation of **1 U = *1 μGy.m^2/h* = *1 cGy.cm^2/h*** is recommended by the AAPM TG 43.

t: Programmed source dwell time.

$t_{ef,\ tr}$: Source effective transit time.

TG: Task Group

TLD: Thermoluminescent dosimeter.

δt: End effect.

Λ: Dose rate constant

CHAPTER ONE – INTRODUCTION

1.1 General Introduction

In radiotherapy, brachytherapy is the treatment of cancer at a short distance using radiation from small radioactive sources. The radioactive material is placed either directly into or near the target volume[1, 2]. Two main types of brachytherapy applications are employed:

- Surface application, in which sources are placed over the tissue to be treated; and
- Interstitial, in which the sources are implanted directly within the tumour volume.

In temporary implants, the sources are removed after the desired dose has been delivered, while in permanent implants, the dose is delivered over the lifetime of the source until it decays completely[2, 3].

Brachytherapy sources are usually inserted into catheters or applicators[1]. When the radioactive sources are transferred to the patient after the insertion of the applicators or catheters, the technique is known as ***afterloading***[1, 3]. The sources can either be transferred by hand (manual afterloading) or automatically (remote afterloading). Remote afterloading technology in HDR brachytherapy is a common treatment modality throughout the world.

1.2 Problem Statement

In the dosimetry of ^{192}Ir high dose rate (HDR) brachytherapy sources, there is an increment of radiation dose (referred to as the transit dose) while the source is in transit to its dwell position, between dwell positions and during retraction back into the safe.

Presently at the Charlotte Maxeke Johannesburg Academic Hospital (CMJAH) and in most HDR brachytherapy units, HDR brachytherapy treatment planning systems ignore the transit dose in the computation of patient dose. Consequently, the absorbed dose to the target volume is more than the prescribed dose as computed during treatment planning. The dosimetric significance of the transit dose is unknown, but it is expected that the effect of the transit dose (depending on its magnitude) may affect clinical outcome[4, 7, 9, 12] under certain circumstances and it should therefore, be known.

The aim of the study was to determine the magnitude of the transit dose component of an ^{192}Ir HDR brachytherapy source and assess its dosimetric significance.

1.3 Study Objectives

This research, aimed at the following:

I. Determination of the effective transit time of two ^{192}Ir HDR clinical remote afterloaders (Nucletron MicroSelectron HDR^{TM} and GammaMed^{TM}).

II. Calculation of the transit dose component of the ^{192}Ir HDR brachytherapy sources.

III. Comparison of the magnitudes of the transit dose obtained from two different measurement techniques, for different source configurations and strengths.

1.4 Radiation Dosimetry

Radiation dosimetry is the determination by measurement and/or calculation of the absorbed dose or some other physically relevant, related dosimetric quantity such as air kerma, fluence or equivalent dose in a medium at a given point of interest[7]. In radiation dosimetry, devices (detectors) that are used to measure dosimetric quantities are called radiation dosimeters. Examples of radiation dosimeters include ionization chambers, thermoluminescent dosimeters (TLDs), calorimeters and Fricke dosimeters (chemical radiation dosimeters). A radiation dosimeter along with its reader is referred to as a dosimetry system. "Measurement of a dosimetric quantity is the process of finding the value of the quantity experimentally using dosimetry systems. The result of a measurement is the value of the dosimetric quantity expressed as a product of a numerical value and an appropriate unit."[2]

Before clinical use, the output of photon and electron beams produced by external radiotherapy machines is calibrated[2]. *Beam calibration is the determination of radiation dose in reference irradiation conditions*. Beam calibration is important as it ensures accurate dose delivery to patients.

For accurate measurement of machine output in radiotherapy, the most practical and most commonly used type of dosimeter is an ionization chamber. The chamber's sensitive volume is filled with ambient air. The dosimetric measured quantity is the ionization charge or current produced in the chamber's sensitive volume. An ionization chamber dosimetry system consists of three main components: a suitable ionization chamber, an electrometer for charge or current measurement and a power supply.

In brachytherapy, dosimetry is concerned with the measurement of source strength specified in reference air kerma rate. This measurement is done through the calibration of the radioactive brachytherapy sources.

1.5 Background and Theory to HDR Brachytherapy

1.5.1 Classification of Brachytherapy Treatments

Brachytherapy treatments can be classified with respect to dose rate[2, 3], treatment duration and source loading[2] as illustrated in Table 1.1.

Table 1.1 Classification of brachytherapy treatments.

Dose Rate	Treatment Duration	Source Loading
Low dose rate (LDR): of the order 0.4 to 2 Gy/h. Medium dose rate (MDR): of the order of 2 to 12 Gy/h. High dose rate (HDR): greater than 12 Gy/h.	Temporary implants: the dose is delivered over a short period of time and the sources are removed after the prescribed dose has been reached. Permanent implants: the dose is delivered over the life time of the source until it decays completely.	Hot loading: the applicator is preloaded and contains the radioactive sources at the time of placement into the patient. Afterloading: the applicator is first placed into the target position, and the radioactive sources are loaded later, either by hand (manual afterloading) or automati-cally (remote afterloading).

Remote afterloaders are available for either low dose rate (LDR) or high dose rate (HDR) treatment[3]. These afterloading systems enable radioactive brachytherapy sources to be transferred remotely into the applicators directly from a shielded storage container (safe) and retracted upon completion of exposure. The principal advantage of HDR over LDR is the convenience of treating on an outpatient basis. The major advantage of remote afterloading over manual afterloading is the reduction of radiation exposure to medical staff.

1.5.2 High Dose Rate Brachytherapy Source Calibration of a Remote Afterloader

In remote afterloading technology, the afterloading system drives the source mechanically to pre-programmed locations (dwell positions) within an applicator and holds it in place for a certain preset time period (dwell time). Such a design is often called a ***stepping source***[1].

^{192}Ir is a radionuclide of choice for HDR brachytherapy photon emitting sources because of its high activity of 10 Ci [1, 5] on delivery. A significant part of quality assurance (QA) programmes for HDR brachytherapy is the source calibration[6]**.** As the radiation dose delivered to a patient requires an overall accuracy of ±5%[2, 14], the calibration of a HDR brachytherapy source is just one of physical procedures aimed at reducing the uncertainty. The end product of source calibration is the determination of source strength from which the prescribed dose is computed. An error in the value of source specification will systematically introduce errors in the delivery of dose to all patients treated with the source.

Manufacturers of ^{192}Ir HDR sources provide a calibration certificate with each newly supplied source, stating the source strength in terms of reference air kerma rate, as at a given date, with a stated uncertainty of up to ±10%[6]. A recalibration of each new source by the end-user (in-house calibration) is required to confirm the vendor's stated value. A percentage difference of not more than ±5% is accepted[3, 11]. "Differences larger than ±5% are not acceptable and would require recalibration by the vendor and issuance of a new calibration certificate"[3]. The source strength value obtained for such an in-house

calibration is used for clinical applications[8]**.** This calibration is performed before patients are treated with the source. With the relatively short half-life (73.83 days) of ^{192}Ir, source replacement three to four times a year is necessary in order to maintain short treatment times[5, 21] and the aim to achieve a high degree of local tumour control. A high activity source is 'hotter' than a low activity source, i.e. the biologic effect caused by a high activity source is greater as compared to a low activity source. Also, as the source decays, the dose rate decreases and the definition of HDR in terms of dose rate becomes invalid. Source activity at replacement is between 3 to 4 Ci[13].

The quantity recommended for the specification of brachytherapy gamma emitting photon sources is the reference air kerma rate [2, 6]**,** defined as the kerma rate to air, in air, at a reference distance of 1 m, corrected for air attenuation and scattering. The SI unit of reference air kerma rate used for the purpose of source specification for HDR applications is μGys^{-1} or $mGyh^{-1}$.

The American Association of Physicists in Medicine Task Group 43 (AAPM TG 43)[14] recommends that photon emitting sources be specified in terms of air kerma strength, $\mathbf{S_k}$. The relationship between reference air kerma rate, $\mathbf{K_R}$ and air kerma strength, $\mathbf{S_k}$ is given by[2, 14]**:**

$$\mathbf{S_k = K_R\,(d_{ref})^2} \quad \text{---------- (1.1)}$$

Where $\mathbf{d_{ref}}$ is the reference distance (1 m) at which the reference air kerma rate is defined. The numerical values of the source strength, whether expressed in reference air kerma rate or air kerma strength, are equal. If the reference air kerma rate of an Ir-192 HDR source is expressed in units of $\mu Gy/h$, then its strength, expressed in air kerma strength is $\mu Gy.m^2/h$. A shorthand notation of **1 U** = $\mu Gy.m^2/h$ = $cGy.cm^2/h$ is recommended by Task Group 43 [14].

With brachytherapy source strength specified in reference air kerma rate or air kerma strength, practical dosimetry is based on the use of ionization chambers that are provided with calibration factors in terms of air kerma.

^{192}Ir HDR brachytherapy sources are calibrated using one of two methods[6]: the free in-air (open-air geometry) measurement technique or using well-type ionization chambers. For the free in-air method, ionization chambers with volumes greater than 0.5 cm^3 (e.g. 0.6 cm^3 Farmer-type) are recommended[6]. For the well-type chamber calibrations, only well-type chambers designed for radiotherapy applications capable of measuring reference air kerma rate of both low and high dose rates are recommended[6]. The active volume of the well ranges from 200 to 1200 cm^3 and typical ionization currents are in the range 10^{-9} to 10^{-7} A for HDR sources[19].

At the Charlotte Maxeke Johannesburg Academic Hospital (CMJAH), both methods are used for source calibration, and the procedures for the calibration are outlined in the International Atomic Energy Agency (IAEA) dosimetry protocol (IAEA-TECDOC-1274)[6]. In either case, the source is brought into the measurement position for a preset period of time **t** (the source dwell time) and the chamber detects the radiation signal emitted from it. The chamber signal is measured by means of an electrometer connected to the chamber. The electrometer reading (ionization charge, **M** or current, **I**) is then converted to reference air kerma rate by using a set of correction factors. The source strength value is entered into the computer treatment planning system from which the dwell positions and dwell times are obtained for each subsequent patient treatment.

1.5.3 The Transit Effect

HDR brachytherapy usually uses a high activity source which afterloads to pre-programmed dwell positions within a catheter for a preset period of time (dwell time). Every HDR application results to two radiation doses: the static dose and the transit dose. This suggests that the total radiation dose delivered during each treatment cycle is equal to the prescribed dose (static) plus the transit dose. During source calibration, the static dose is the dose measured by the detector when the source is stationary at a measurement position (dwell position), whereas the transit dose is an additional radiation dose component detected while the source moves from its shield to the dwell positions, and then during retraction after the measurement[6] repeated for each catheter and channel. Because the transit effect depends on a number of factors, it is often quantified by means

of an effective transit time and so accurate measurement of the effective transit time of a HDR brachytherapy source is necessary in order to compute the total radiation dose given to the target volume[4]

1.5.4 Patient Dose Computation

Dose distributions around a linear ^{192}Ir source used in HDR afterloaders are calculated using a number of methods[3], such as the Sievert integral, TG-43 formalism or Monte Carlo methods**.**

The TG-43 formalism has advantages over the Sievert integral approach in that the effects of various physical aspects of the dose distribution are considered separately and the dosimetric quantities involved can be individually measured or calculated using Monte Carlo methods[3].

In patient dose computation, either the dose rate or duration of treatment time is determined[15]. For a point source of ^{192}Ir and according to the TG-43 formalism, the dose rate $\check{D}_R(r)$ at point R from the point source is given by[3, 14, 15, 17]**:**

$$\check{D}_R(r) = \Lambda * S_k / r^2 \quad \text{---------- (1.2)}$$

where **r** is the radial distance from the source position to point R in the medium, Λ is the dose rate constant for the source in units of dose rate in the medium (water) per unit air kerma strength (**cGyh^{-1}U^{-1}**), and S_k is the air kerma strength in units of ***cGy.cm^{2}h^{-1}*** **(U),** **(**where **1 U =** ***1 μGy.m^{2}h^{-1} = 1 cGy.cm^{2}h^{-1}***). Practically, r is measured from the centre of the source at each dwell position. The dose rates calculated by Eq. (1.2) at various dwell positions are multiplied by the corresponding dwell times and summed to give the total treatment dose.

The values of Λ that have been calculated by two commercially available HDR sources using Monte Carlo codes are[3], **1.044 cGyh^{-1}U^{-1}** for the GammaMed afterloader and **1.115 cGyh^{-1}U^{-1}** for the Nucletron microSelectron HDR afterloader. If the air kerma strength S_k is quoted in units of apparent activity (**mCi**), the dose rate constant Λ has units of **cGyh^{-1}.mCi^{-1}.**

1.5.5 Critical Analysis of Literature

A number of contributions have been made to transit dose/time determination and some techniques have been proposed for the correction of source transit in the calibration of ^{192}Ir HDR brachytherapy sources[4 – 7, 9, 12, 16, 18].

Sanjay et al[4] measured the transit time of a Gammamed HDR brachytherapy unit during source movement between two dwell positions. A well-type ionization chamber and an electrometer were used to measure the charge generated during the movement of the ^{192}Ir source through an interstitial needle. The charge was measured with the source programmed to dwell for different amounts of time at two separate locations, X_1 and X_2 along the needle. Locations X_1 and X_2 were chosen between 1 and 15 possible dwell positions of the source using a step size of 10 mm. Measurement of charge q_1 was first made with the source at X_1 for time t_1 (5, 10, 15 and 20 s). Then six measurements of charge q_2 were made with the source at X_1 for t_1 and then moved to X_2 for time t_2 (5, 10, 15, 20, 25, and 30 s). The net charge, q_n generated during source movement from X_1 to X_2, and for the source dwelling at X_2 was calculated from

$$\mathbf{q_n = q_2 - q_1} \quad \textbf{(1.3)}$$

A linear regression analysis of q_n as a function of t_2 was made to express q_n as

$$\mathbf{q_n = I.t_2 + q_0} \quad \textbf{(1.4)}$$

where **I,** the slope of the linear fit was the charge per unit time or current and $\mathbf{q_0}$, the intercept on the charge axis was the charge generated during source transit between two dwell positions. The effective transit time was calculated from the equation

$$\mathbf{t_{ef,\,tr} = q_0 / I} \quad \textbf{(1.5)}$$

Values of the transit time were determined by the above procedure for four different values of $\mathbf{t_1}$ (5, 10, 15, and 20 s) at $\mathbf{X_1}$. The dwell times were chosen arbitrarily with the upper limit dictated by the limitation of the electrometer. The effective transit times were 0.129, 0.182, 0.301, 0.402, 0.701, and 0.993 s. 1, 2, 4, 6, 8 and 10 cm inter-dwell separations respectively were used. In this study, Sanjay did not assess the dosimetric or clinical significance of the transit time as the study concluded that the results obtained were not intended for use clinically because of the uncertainties associated in the measurement. In addition, only the inter-dwell transit times were determined. The transit

time for the total travel of the radioactive source into (entry) and out of (exit) of an applicator was not measured.

Goetsch et al[5] proposed that the correction for source transit could be treated as a shutter-timer error, given that the size of the correction depends on the source-to-detector distance (SDD), as well as the proximity of the catheter to the chamber. Goetsch et al[5] used a cavity chamber and constructed a separate electronic timer that supplied trigger pulses to a digital voltmeter, connected to a unity-gain output of an electrometer, in a manner that allowed repeated exposures to be made while the source remained fixed in position. Pressing the START button freezed the initial voltage reading and started the timer. At the end of a preset time interval, the final voltage was displayed. The charge accumulated during the time interval was obtained by subtracting the initial from the final voltage reading, and multiplying the result by the calibrated electrometer capacitance.

The IAEA-TECDOC-1274[6] proposes some techniques that could be used to eliminate the transit component of the signal, emphasising that the magnitude of the transit signal depends strongly on the source-to-detector distance (SDD), and could be significant at the distances recommended for calibration. Two of the techniques proposed are:

- Using an externally-triggered electrometer to collect charge during an interval after the source has stopped moving. This technique is equal to the method used by Goetsch et al[5]**.** This is an efficient method as the dosimeter only measures a signal while the source is stationary. The disadvantage is that the use of external timers with digital voltmeters in the auto-ranging mode will introduce significant errors[5]. Thus it is advisable to use digital voltmeters in the fixed range to avoid these auto-ranging time errors.
- Subtracting two readings taken for differing intervals of time to eliminate the transit charge common to both. This technique is not accurate as it uses only two readings. A whole range of time measurements of clinical interest should be used for accuracy.

Carmen et al[9] used an alanine-EPR (electron paramagnetic resonance) dosimetric system to evaluate the transit dose of an HDR system. The work predicted that the transit dose absorbed by the tumour and surrounding tissues depends linearly on the strength of the radioactive source, on the number of times (n) that the source enters and exits its static position and on its velocity along the trajectory. A device II used for the experimental dose determination held ten pairs of alanine dosimeters positioned symmetrically at 1 cm intervals and 5 mm distant from the centre of the source trajectory for entry to and exit from the static position. For one round trip of the source, a given dosimeter pair measured a dose that was the sum of the transit dose and the static dose. A second dose observation was made after **n** round trips in which the source delivered the same static dose as in the first experiment, but the transit dose was n times greater. The transit dose at each of the ten positions was related to the difference of the two observations. The results showed that for a point 5 mm equidistant from four needles inserted into a target volume and for a source of 10 Ci delivering 12 irradiation fractions of 300 cGy each, the transit dose would be 5% of the total prescribed dose at this point. The study concluded that the transit dose should be taken into account in patient brachytherapy treatment planning. This approach measured the transit dose along an interstitial needle directly. The approach however cannot be used in routine clinical calibrations because of the complexity and cost involved using alanine/EPR dosimetry.

Bastin et al (1993), (cited by Sanjay et al[4]) measured the transit dose produced by a moving HDR source and assessed its clinical significance. A Lucite phantom accommodating calibrated thermoluminescent dosimeter (TLD) rods, an endobronchial applicator, esophageal and endobronchial catheters, a gyneacological tandem and an interstitial needle were used in the measurements. The transit dose at 0.5 cm from an endobronchial catheter was 0.31 cGy/(Curie-fraction) and followed an inverse fall-off with increasing distance. Surface transit doses were also measured which ranged from 0.38 cGy/(Curie-fraction) for the esophageal catheter to 1.03 cGy/(Curie-fraction) for the endobronchial catheter. The study predicted that the total transit dose was dependent on the source velocity, the number of treatment fractions and the source strength, while surface transit doses were dependent on the applicator diameter, wall material and

thickness. The study concluded that the total transit doses within or outside the treatment volume were less than 100 cGy, but may exceed 200 cGy when using a large number of fractions with a high activity source.

From the conclusions made by Bastin et al and Carmen et al[9], the transit dose is strongly dependent on source activity, fractionation and the number of times that the source enters and exits its static position. The dependence of the transit dose on fractionation strongly supports the point that the transit dose depends on the number of times that the source enters and exits its static position[9].

Wong et al[7] investigated the effects of the transit dose in the target volume of a HDR brachytherapy stepping source. A video camera was used to capture and analyse the entrance, exit and the inter-dwell transit speed of the source for different path lengths and step sizes ranging from 2.5 mm to 995 mm. The transit speed was found to vary with the step size and path length. For distances travelled of 2.5, 5.0, 10.0 230, and 995 mm, the average transit speeds were 54, 72, 233, 385 and 467 mm/s respectively.

A well-type chamber was also used in Wong et al's[7] study to determine the dose difference between two sets of measurements, one being the stationary dose only and the other the sum of stationary and transit doses. Single catheters of active lengths of 20 and 10 mm, different dwell times of 0.5, 1, 2 and 5 s and different step sizes of 2.5, 5 and 10 mm were used in the measurements with the well-type chamber. Most of the measured dose differences between stationary and stationary plus inter-dwell source movement were within 2%. The additional dose due to the source transit was as high as 24.9% of the static dose for the case of 0.5 s dwell time, 10 mm step size and 20 mm active length. The study concluded that the transit dose of a MicroSelectron HDR afterloader was mainly made up of the entry and exit components, but not the inter-dwell transit dose component, as the inter-dwell component was accounted for by the afterloader itself.

Sang-Hyun and Muller-Runkel, and Nath et al 1995 (cited by Carmen et al[9]) concluded that the transit dose can be 5% higher than the prescribed absorbed dose value, but it should not exceed this percentage clinically.

Thomadsen[12] proposes that the source 'equivalent' transit time can be determined from a multiple exposure technique. In this technique, two exposures are made: one exposure, $\mathbf{R_s}$ for a specified timer setting, and a second, $\mathbf{R_m}$ for the same overall time, but broken into a number, **m** of shorter exposures. The equivalent transit time is given by:

$$\mathbf{t_{eq} = (R_s - R_m)/ (I - mI)} \quad \textbf{(1.6)}$$

where **I** is the electrometer reading rate or charge rate. The value of the current, I is determined from several measurements, $\mathbf{R_i}$ for various times, $\mathbf{t_i}$. With the assumption that $\mathbf{t_i}$ increases as **i** increases, then for adjacent pairs of readings,

$$\mathbf{I = (R_{i+1} - R_i)/ (t_{i+1} - t_{i)}} \quad \textbf{(1.7)}$$

The value of I in Eq (1.6) which is obtained from Eq (1.7) should be the average value of at least six different source transfers. In Eq (1.6), the single exposure contains one transit, while the 'multiple exposure' contains m transits.

The multiple exposure technique adopted by Thomadsen[12] is accurate as several relative measurements are used to calculate the transit time. But Thomadsen noted that the equivalent transit time varies with the measurement geometry, so measurements with a well chamber give different transit times from those made with a thimble ionization chamber. He noted further that neither the well-type chamber method nor the open-air geometry technique gives the true transit time, but that any measured equivalent transit time serves as a baseline for changes in the source transit over time.

The American Association of Physicists in Medicine (AAPM) Task Group No. 41 (TG 41)[16] recommends that the correction for source transit time can be treated as an end effect as follows:

$$\mathbf{I = M_t / (t + \delta t)} \quad \textbf{(1.8)}$$

where **I** is the charge rate or current, $\mathbf{M_t}$ is the charge collected per unit time with the source at a fixed calibration distance d, **t** the source dwell time and **δt** is the end effect,

the transit time of the source and a function of d. The charge rate is obtained from a linear regression analysis of integrated charges for different time intervals (dwell times). The TG 41 report notes further that the linear regression should be done for each distance as the fractional contribution to source transit increases with source-to-chamber distance (SCD). Alternatively, TG 41 proposes that the charge collection rate can be taken as equal to the difference between two timed measurements divided by the difference between the corresponding times. The subtraction of two integrated charges eliminates the contribution from source transit because it is independent of time.

As noted earlier, this method may not be very accurate as it uses only two measurement points. Eq (1.8) uses linear regression with several measurements and improves the accuracy in transit time determination as the dwell times used for the measurements should be taken over the range of clinical interest.

Wojcicka et al[18] examined the transit dose components of three commercially available HDR systems (microSelectron-HDR (Nucltron-Oldelft), Omitron 2000 and GammaMed 12i) using a technique based on film dosimetry. A comparison of the transit dose components for all three HDR systems revealed that the largest transit dose was measured for the Omitron system. The smallest transit dose component was for the Nucletron-Oldelft system. The results of the study showed that for a typical head and neck treatment scheduled for five days, two fractions per day with a source strength of 10 GBq, tissues within and outside the treatment volume could be expected to receive at least 277 cGy of transit dose if the patient was treated on the Omitron system compared to 83 cGy on the GammaMed 12i and 66 cGy on the Nucletron-Oldelft systems.

As values of the transit times and percentage values of transit dose investigated in the various studies differ, it is clear that the transit effect is different for different HDR brachytherapy units[7, 18] depending on the remote afterloading technology used (Omitron, Gammamed Plus, MicroSelectron Classic, MicroSelectron HDR, Varian and VariSource). According to the literature review, the transit effect also varies with the source activity, setup geometry, measurement distance (SCD), source configuration and

the type of ionization chamber used (thimble or well-type chamber), i.e. the measurement technique. It is therefore necessary for the end-user of each HDR brachytherapy unit to determine the transit dose of their HDR afterloader and assess its dosimetric significance to their clinical practice.

CHAPTER TWO – MATERIALS AND METHODS

2.1 Research Materials

2.1.1 Dosimetry Systems

Two calibrated ionization chambers and electrometers were used for charge measurements.

- A 0.6 cm^3 cylindrical thimble therapy (Farmer-type) ionization chamber (PTW M30001) and a PTW UNIDOS E electrometer (Model No. T10008).
- A Standard Imaging Well-type ionization chamber (Model No. 90008) with an active volume of 245 cm^3 and a CDX – 2000B electrometer

Figures 2.1 and 2.2 are photographs of the two dosimetry systems.

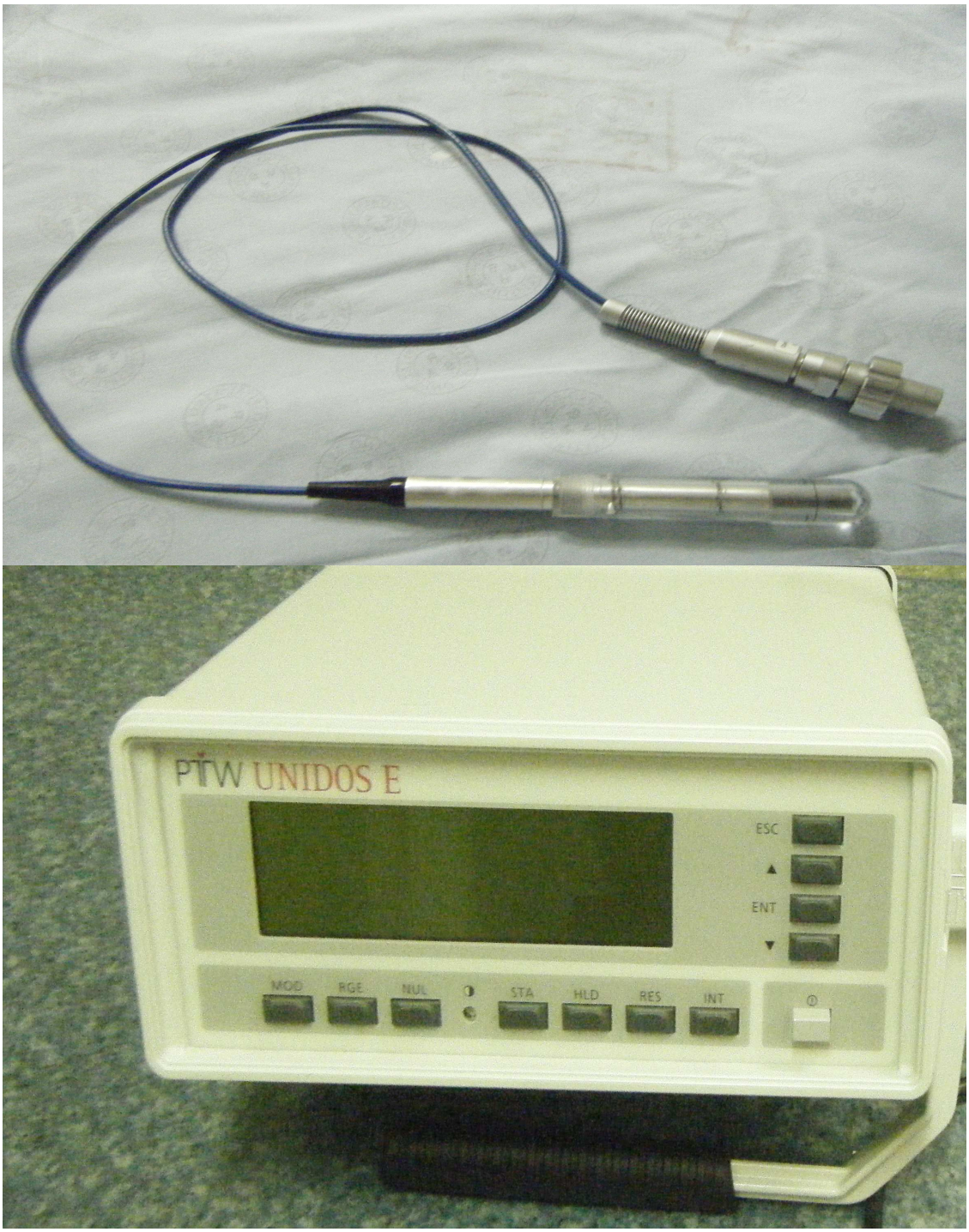


Figure 2.1 A thimble (0.6 cc Farmer-type) ionization chamber with build-up cap (top) and the PTW UNIDOS E electrometer (bottom).

Figure 2.2 A Standard Imaging HDR 1000 Plus Brachytherapy well-type ionization Chamber (top) and the CDX-2000B Standard Imaging Electrometer (bottom).

2.1.2 Remote Afterloading Equipment

Two ^{192}Ir HDR brachytherapy units (Nucletron microSelectron HDR and GammaMed) were used. The shortest programmable dwell time for both units is 0.1 s.

Figures 2.3 and 2.4 are photographs of the microSelectron and GammaMed remote afterloaders respectively.

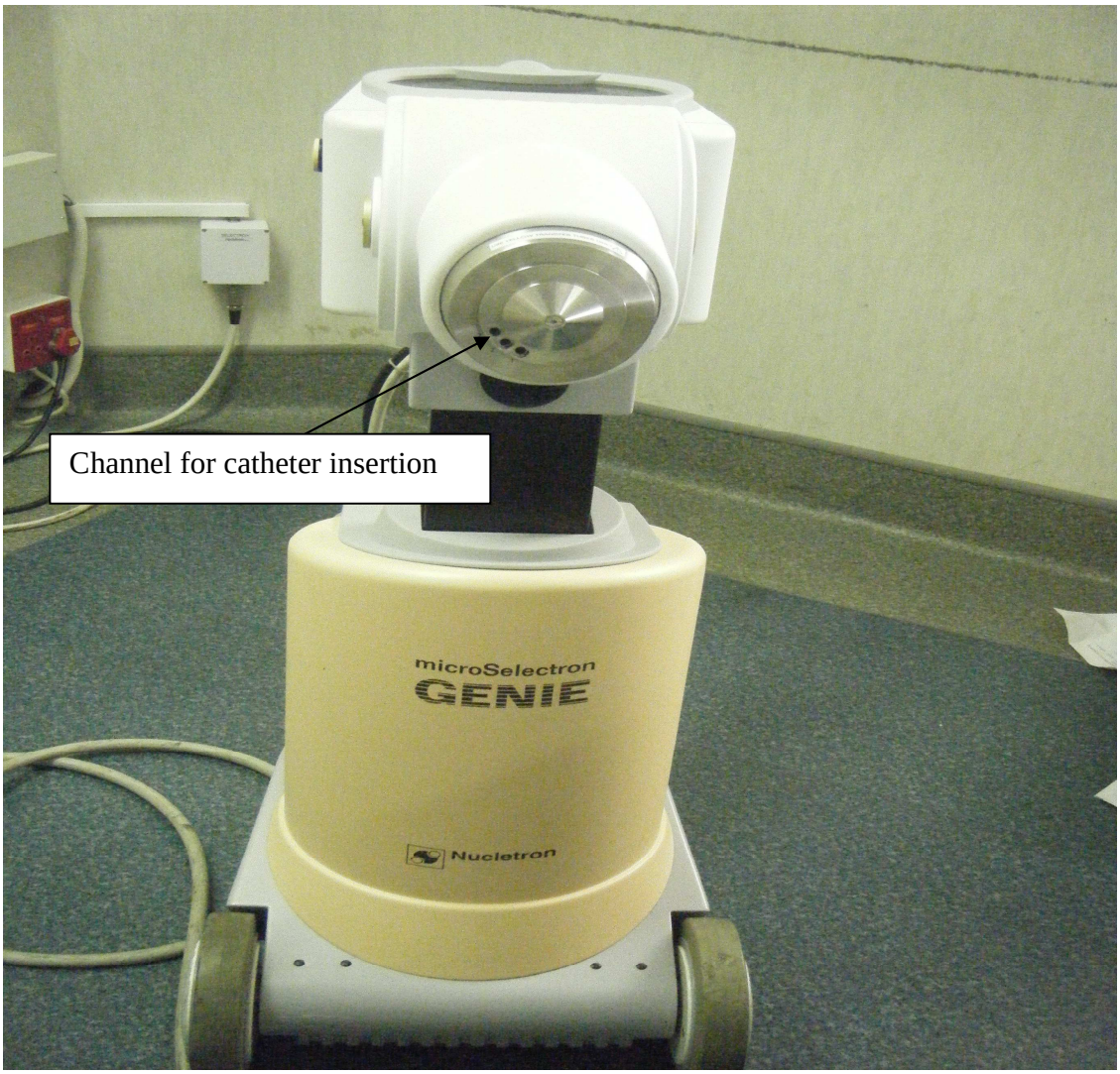


Figure 2.3 A Nucletron microSelectron HDR remote afterloader

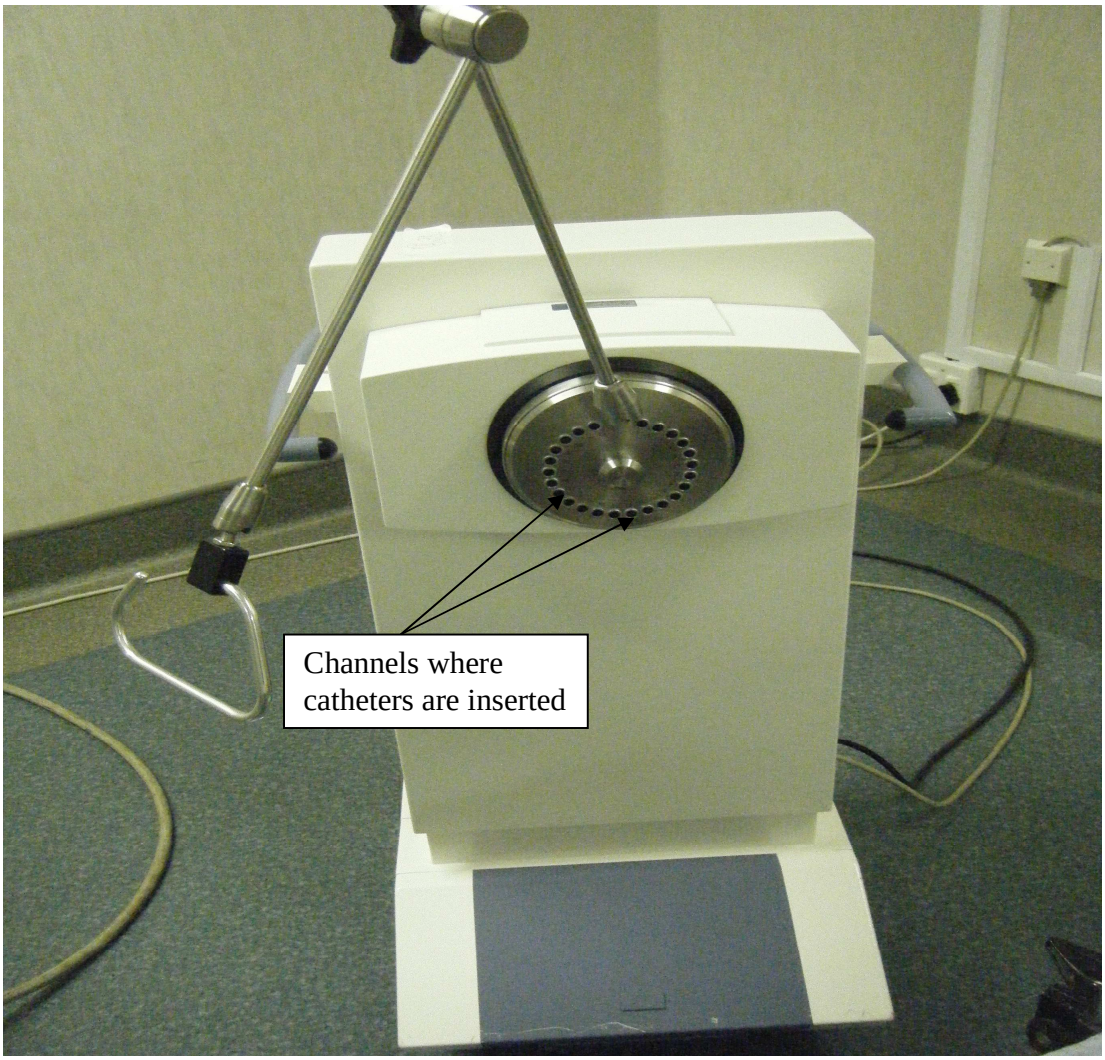
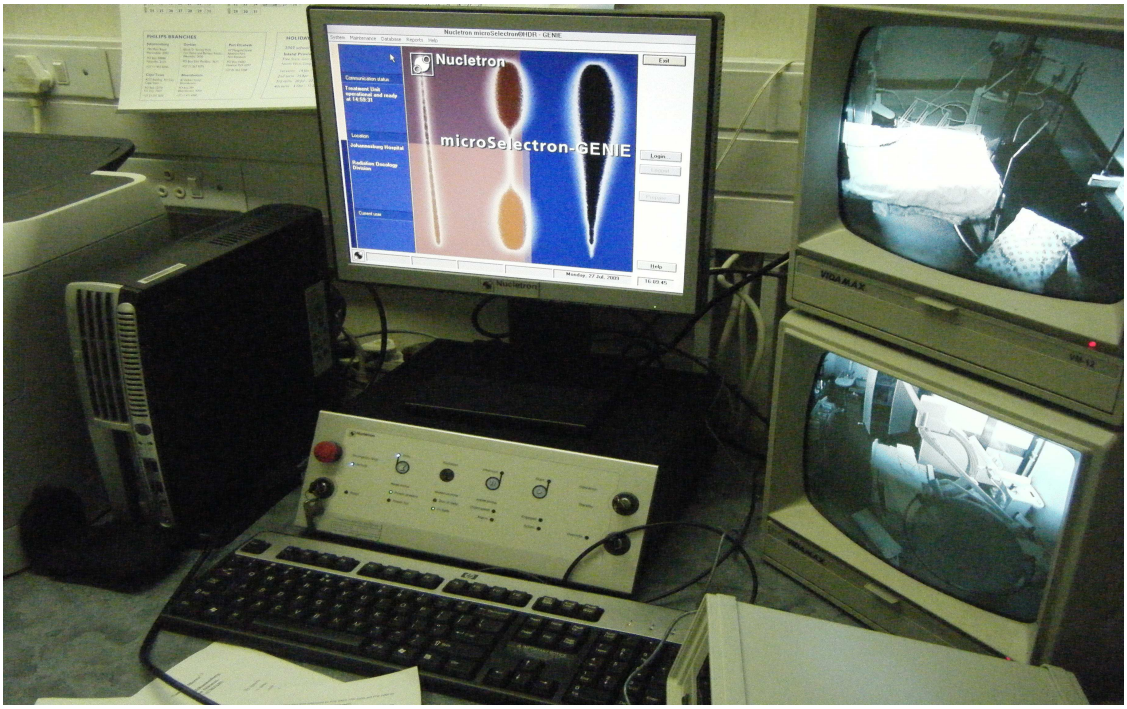
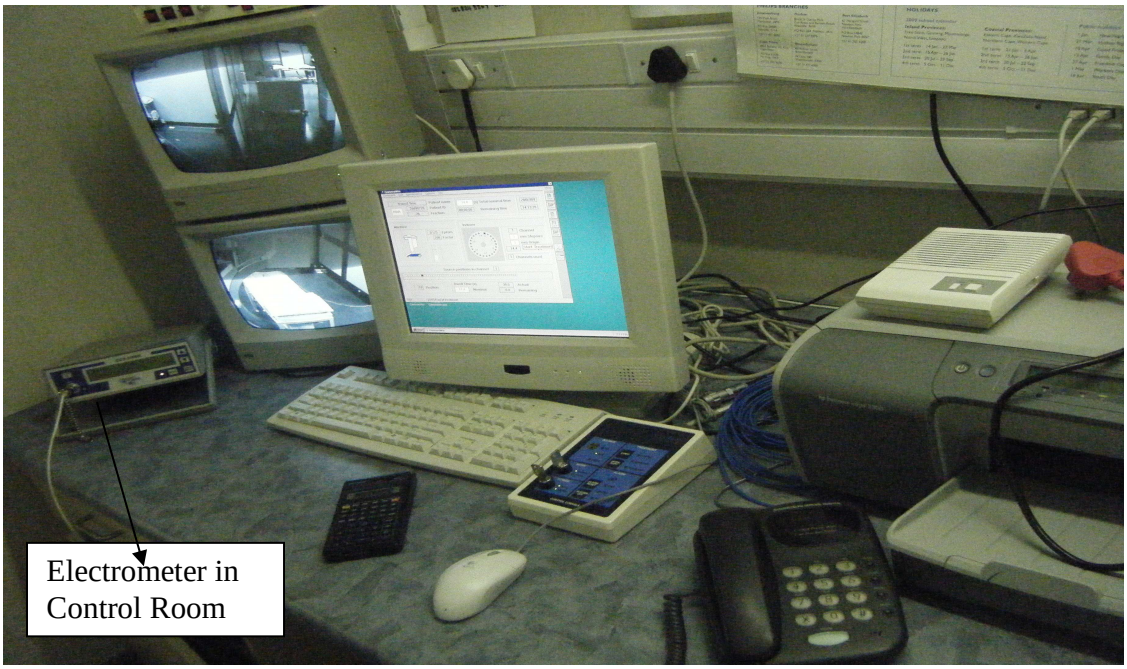


Figure 2.4 A GammaMed remote afterloader for HDR brachytherapy application.

A computer workstation in each HDR brachytherapy unit's control room was used for programming the dwell times and positions. Figure 2.5 shows photographs of the two HDR brachytherapy units' control rooms.



(a)



(b)

Figure 2.5 HDR brachytherapy units' Control Rooms: (a) Nucletron microSelectron HDR and (b) GammaMed. The workstations were used for programming the dwell times and positions during the measurements.

2.2 Data Collection Procedures and Measurement Techniques

2.2.1 Introduction

Data were collected over a period of four months (from May to August in 2009) for different source activities.

2.2.2 Experimental Setups for Integrated Charge Measurements

Two different measurement techniques were used as recommended by the IAEA-TECDOC-1274[6] approach for the calibration of ^{192}Ir brachytherapy sources. The techniques used were the open-air geometry measurement method using the 0.6 cc Farmer-type ionization chamber and the well-type chamber measurement technique.

Setup Geometry for Measurements with the Farmer-type ionization chamber

For measurements made with the 0.6 cm^3 chamber, a mounting device (a jig) made of low density plastic was used to hold the chamber and the source in fixed positions during measurements. Measurements were done at four different source-to-chamber distances (SCD) of 5, 10, 15 and 20 cm. A photograph of the jig is shown in Figure 2.6.

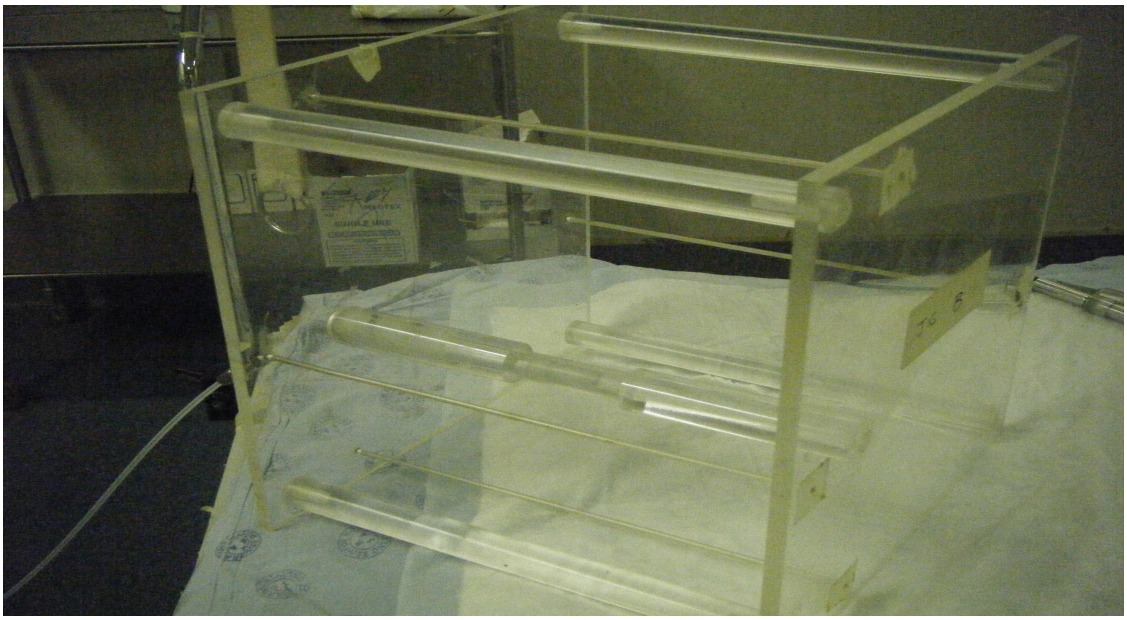


Figure 2.6 A Jig made of low density plastic. Its designed is such that it minimizes radiation scatter and positional uncertainty. It was used to hold the 0.6 cm^3 chamber and the radioactive brachytherapy source in fixed positions during measurements.

Setup Geometry for Measurements with the well-type chamber

For the well-type chamber method, the source was inserted and positioned at the calibration point (position of maximum response) of the chamber since the charge reading is dependent on the position of the source in the well[3, 6, 19, 20].

In both the free in-air and the well-type chamber measurement techniques, the electrometer was placed in the HDR brachytherapy unit control consol while the ionization chamber was placed in the treatment room near the afterloader. The radioactive sources were transferred from the HDR remote afterloaders to the measurement positions using single catheters (transfer tubes) of length 120 cm each in both HDR units. All practical effort was made to reduce room radiation scatter by placing the chambers at least 1 m from scattering surfaces such as walls, ceilings, floors and nearby scattering objects that might scatter radiation back to the chamber.

Figure 2.7 is a photograph of the transfer tubes.

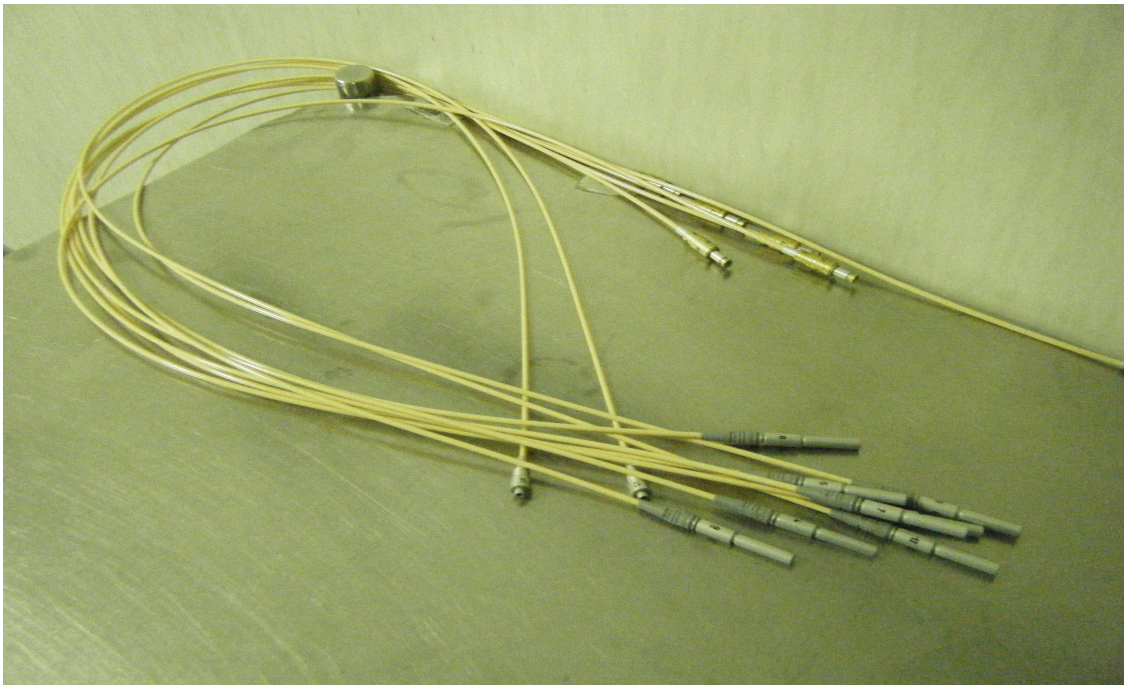


Figure 2.7 The transfer (guided) tubes used to transfer the ^{192}Ir radioactive source to its dwell position for exposure.

Figure 2.8 shows the complete experimental setup for the open-air geometry measurement method at the microSelectron HDR unit.

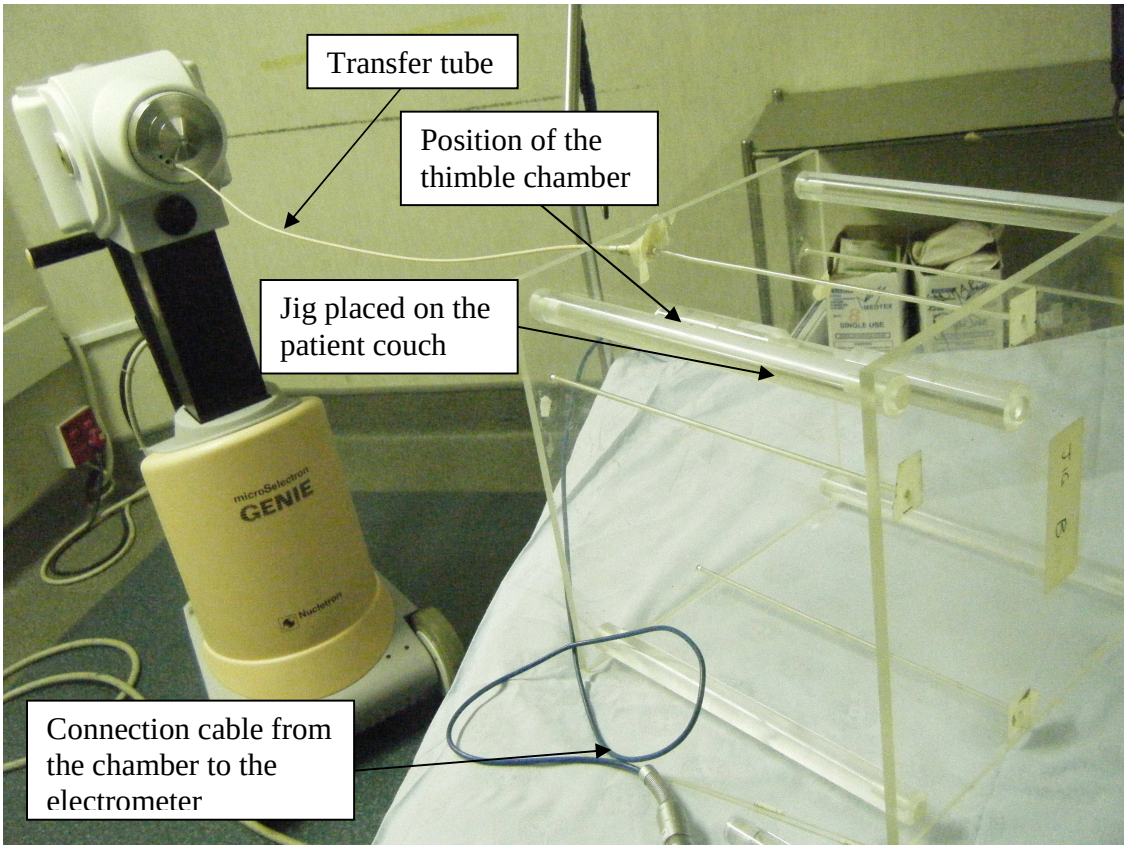


Figure 2.8: The open-air geometry setup method with the source transfer tube connected to the Nucletron MicroSelectron HDR remote afterloader and fixed to the jig showing the position of the thimble ionization chamber. One can see the position of the catheter from one of the channels of the afterloader to the jig and the position of the thimble chamber in the jig. A catheter of length 120 cm was used for both the microSelectron HDR and GammaMed afterloaders.

Figure 2.9 is a photograph illustrating the complete experimental setup for the well-type chamber measurement technique at the GammaMed unit. The source was inserted and positioned at the calibration point of the chamber using a transfer tube of length 120 cm.

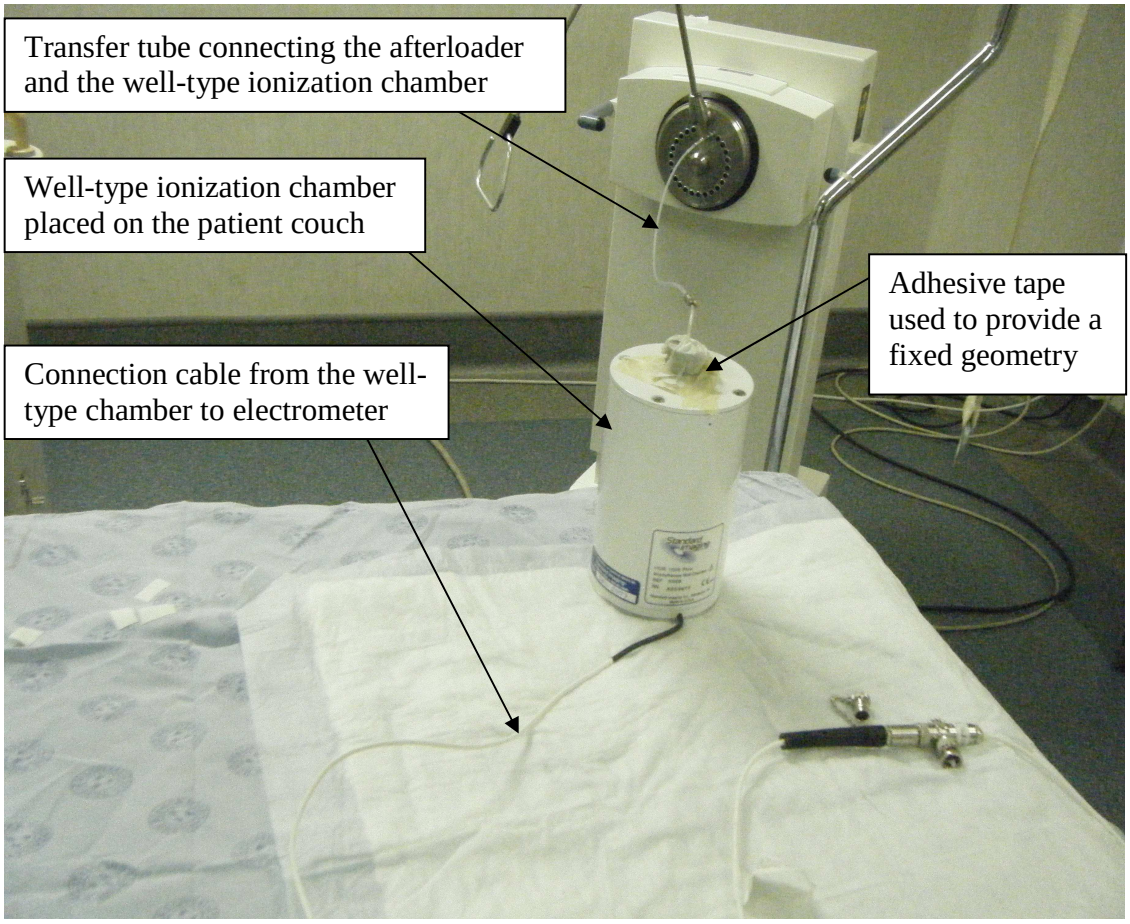


Figure 2.9: The well-type ionization chamber measurement technique at the GammaMed unit. The well-type chamber is placed on a patient couch near the afterloader. The source is transferred to the "sweet spot" of the chamber since the charge reading is dependent on the position of the source in the well.

2.2.3 Source Transfer Mechanism and Source Configurations for Charge Measurements

Integrated charge was measured for the total transit of the ^{192}Ir radioactive source into (entry) and out of (exit) the catheters. Measurements were made during the months of May, June, July and August in 2009.

Different source configurations were used for the measurements. Two exposures of integrated charge were made: a single exposure $\mathbf{M_s}$ was made for a programmed source

dwell time of 120 s, and a ‘multiple exposure’ $\mathbf{M_m}$ was made for the same overall dwell time, but split into two to five short exposures of **m**.

The measurements were taken at a single dwell position (the sweet spot of the chambers) or at three different dwell positions including the sweet spot. The single exposure was achieved by programming the source to move in and out of the catheter once (i.e. there was only one source transfer from the safe) for the total dwell time of 120 s. For the case where measurements were taken at three different dwell positions, the source commenced at the most distal dwell position and stepped backwards. A Step size of 10 mm was used. The ‘multiple exposure’ was achieved by programming the source to travel in and out of the catheter three times for the case where the measurements were done at three different dwell positions. Each transfer was done for a programmed dwell time of 40 s. For the case where split measurements were done at the sweet spots only, three source transfers of 40 s each were used at the microSelectron HDR unit and four transfers of 30 s each at the GammaMed unit. In both cases, the electrometer displayed the total integrated reading when the transfers were complete.

For the three source configurations, only the well-type chamber was used. The measurements in this case were only done in August 2009.

Figure 2.10 shows a diagrammatic representation of the single source configuration for measurements at the sweet spots only, whereas Figure 2.11 shows the configuration for measurements at three different dwell positions.

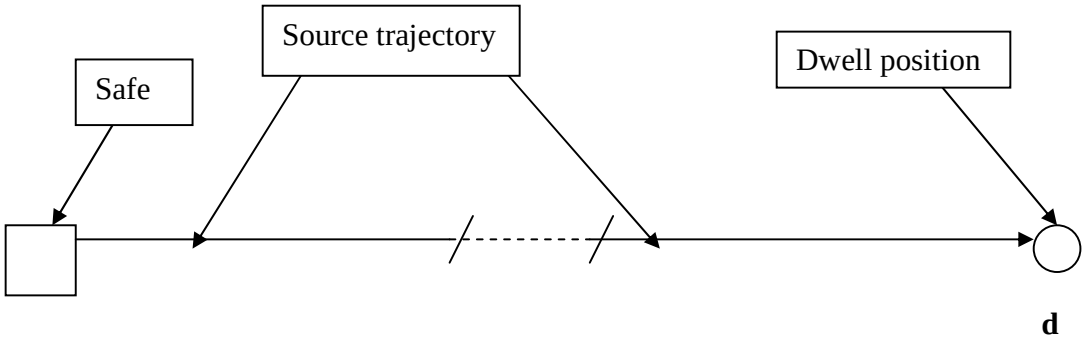


Figure 2.10: The single source transfer configuration used for measurements at the sweet spots only. Position d represents the sweet spot. The source travels from the safe to position d for a preset time t after which it retracts back into the safe.

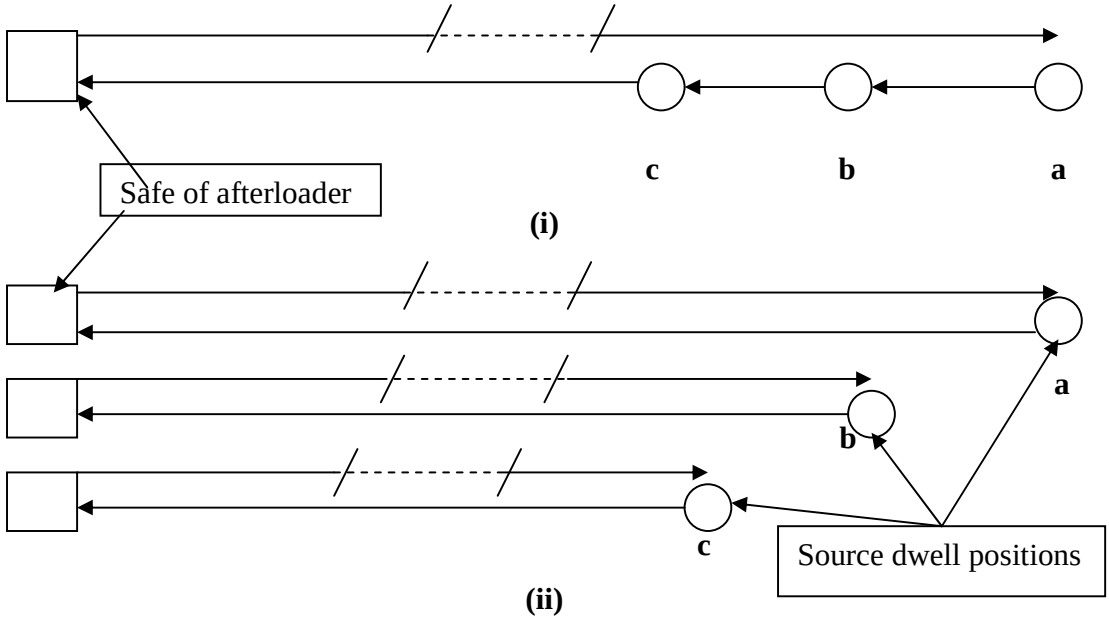


Figure 2.11: The configurations for the measurements at three different source positions **a**, **b** and **c**, with position **b** being the sweet spot. There are two situations: **(i)** The source travels from the safe to the most distal dwell position **a** and then steps backward to position **b** and then **c**; and **(ii)** There were three independent source transfers, with one transfer to each dwell position **a**, **b** or **c**.

Apart from the multiple exposure technique, relative measurements of integrated charge were also taken at the positions of maximum response of the chambers for different amounts of time. Integrated charge was collected by programming dwell times in the

range of 15 to 135 s and 20 to 160 s for the GammaMed and microSelectron units respectively. With this approach, the dwell times were chosen arbitrarily over the range of clinical interest with the upper limit being dictated by the limitation of the electrometer. For the GammaMed unit and using the well-type chamber measurement technique, the Standard Imaging CDX-2000B electrometer could not read charge beyond 135 s for a source activity of 9.3 Ci. The 135 s limit was therefore also applied to the open-air geometry method since one of the objectives of this study was to compare the results obtained for the two measurement techniques. Similarly, for the microSelectron unit, the upper limit was found to be 160 s for a source activity of 8.6 Ci.

2.3 Analysis Techniques for Transit Time Determination

Two techniques were used to determine the transit time: a multiple exposure technique and a graphical technique.

2.3.1 The Multiple Exposure Technique

The multiple exposure technique was used for transit time determination. From two exposures of integrated charge (a single exposure $\mathbf{M_s}$ made for a dwell time of 120 s, and a 'multiple exposure' $\mathbf{M_m}$ made for the same overall time, but split into **m** short exposures), the source effective transit time is given by:

$$\mathbf{t_{ef,\,tr} = (M_m - M_s)\, t \,/\, (mM_s - M_m)} \quad \text{---------- (2.1)}$$

where, **m** was four at the GammaMed unit and three at the microSelectron HDR unit for measurements at single dwell positions. For measurements at three different source positions, **m** was three at each unit.

2.3.2 The Graphical Solution of Zero Exposure

A graphical solution was also used for transit time determination. This technique used several charge readings, measured for different time intervals of 15 s at the GammaMed unit and 20 s at the microSelectron HDR unit. Nine measurements were made at each unit. The measurements were then linearly regressed and extrapolated to obtain the transit time.

2.4 Calculation of Transit Dose

The transit dose components of the ^{192}Ir HDR brachytherapy sources were derived from the relative values of the measured transit time for different values of source strength, dwell time, prescription dose, and different source configurations.

The dosimetric significance of the transit dose was assessed by calculating (as a percentage) the fractional contribution of the transit dose to a typical prescription or treatment dose (static dose) for different values of source strength and dwell time.

CHAPER THREE – RESULTS

3.1 Integrated Charge Measurements

Sources of uncertainties in the measurements are discussed in Appendix A. The uncertainties in the charge measurements were minimized by taking three successive readings for each programmed source dwell time with the same setup. The three successive measurements were then averaged to obtain a mean value for each programmed source dwell time.

3.1.1 Multiple Exposure Technique

The results of the charge measurements using the multiple exposure technique are presented in Tables 3.1 and 3.2 for both measurement techniques for the GammaMed and MicroSelectron HDR units respectively.

Table 3.1 Electrometer readings for the **(a)** well-type chamber and **(b)** thimble chamber using the multiple exposure technique at the GammaMed unit during the months of May, June, July and August in 2009. Only the well-type chamber method was used in August 2009. $\mathbf{M_s}$ is the result from a single exposure made for a preset time **t** of 120 s and $\mathbf{M_m}$ is from the multiple exposure made in four short exposures of 30 s each. SCD is the source-to-chamber distance.

(a)

MAY		JUNE		JULY		AUGUST	
$\mathbf{M_s}$ **(nC)**	$\mathbf{M_m}$ **(nC)**	$\mathbf{M_s}$ **(nC)**	$\mathbf{M_m}$ **(nC)**	$\mathbf{M_s}$ **(nC)**	$\mathbf{M_m}$ **(nC)**	$\mathbf{M_s}$ **(nC)**	$\mathbf{M_m}$ **(nC)**
8542.1	8856.1	5960.6	6195.0	4117.3	4294.3	**6619.3**	**6805**

(b)

SCD (cm)	MAY MEASUREMENTS		JUNE MEASUREMENTS		JULY MEASUREMENTS	
	$\mathbf{M_s}$ **(nC)**	$\mathbf{M_m}$ **(nC)**	$\mathbf{M_s}$ **(nC)**	$\mathbf{M_m}$ **(nC)**	$\mathbf{M_s}$ **(nC)**	$\mathbf{M_m}$ **(nC)**
5	8.888	9.165	6.297	6.493	4.520	4.647
10	2.267	2.346	1.575	1.636	1.168	1.210
15	1.013	1.052	0.691	0.718	0.513	0.530
20	0.569	0.585	0.396	0.410	0.286	0.291

Table 3.2 Electrometer readings for the **(a)** well-type chamber and **(b)** thimble chamber using the multiple exposure technique at the microSelectron HDR unit during the of May, June, July and August in 2009. Only the well-type chamber method was used in August 2009. $\mathbf{M_s}$ is the result from a single exposure made for a preset time **t** of 120 s and $\mathbf{M_m}$ is from the multiple exposure made in three short exposures of 40 s each. SCD is the source-to-chamber distance.

(a)

MAY		JUNE		JULY		AUGUST	
$\mathbf{M_s}$ (nC)	$\mathbf{M_m}$ (nC)	$\mathbf{M_s}$ (nC)	$\mathbf{M_m}$ (nC)	$\mathbf{M_s}$ (nC)	$\mathbf{M_m}$ (nC)	$\mathbf{M_s}$ (nC)	$\mathbf{M_m}$ (nC)
7490.7	7535.7	5377.2	5409.5	3870.2	3893.1	8127.8	8154.8

(b)

SCD (cm)	MAY MEASUREMENTS		JUNE MEASUREMENTS		JULY MEASUREMENTS	
	$\mathbf{M_s}$ (nC)	$\mathbf{M_m}$ (nC)	$\mathbf{M_s}$ (nC)	$\mathbf{M_m}$ (nC)	$\mathbf{M_s}$ (nC)	$\mathbf{M_m}$ (nC)
5	7.777	7.812	5.738	5.764	3.944	3.960
10	2.009	2.020	1.435	1.444	1.026	1.031
15	0.889	0.894	0.644	0.652	0.457	0.461
20	0.506	0.508	0.363	0.365	0.262	0.264

3.1.2 Relative Measurements for different amounts of time

This approach used several relative measurements of integrated charge taken at the sweet spots of the chambers for different amounts of time. Integrated charge was collected by programming dwell times in the range of 15 to 135 s and 20 to 160 s for the GammaMed and microSelectron units, respectively. The results were analysed graphically and linearly extrapolated to zero exposure (charge) on the charge-axes to obtain the transit times as intercepts on the time-axes given in section 3.2.

Figure 3.1 shows the straight line relationship between charge and source dwell time for measurements with the well-type chamber at the GammaMed unit during the months of May, June and July in 2009 and Figure 3.2 similarly shows the relationship from the measurements with the Farmer-type chamber at the microSelectron HDR unit during the month of May in 2009.

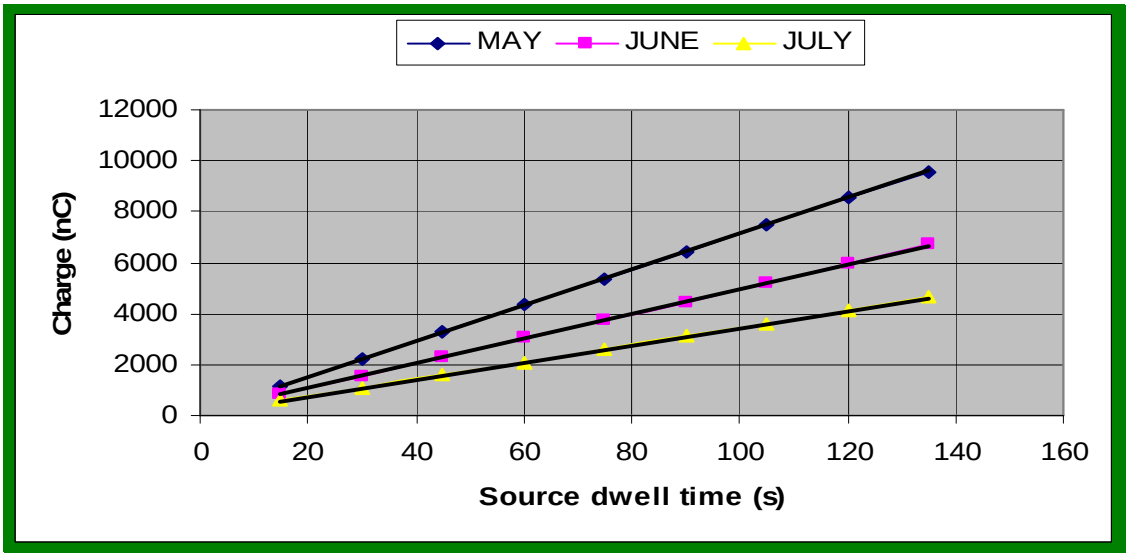


Figure 3.1 The straight line relationship between the charge and source dwell time for measurements with the well-type chamber at the GammaMed unit during the months of May, June and July in 2009.

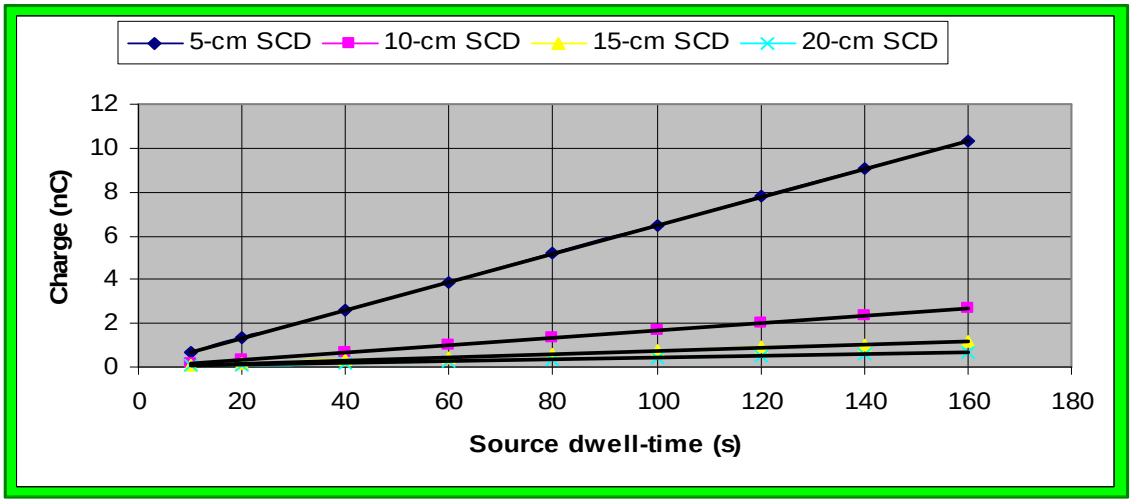


Figure 3.2 The straight line relationship between the charge and source dwell time for measurements with the Farmer-type chamber at different source-to-chamber distances (SCDs) of 5, 10, 15 and 20 cm at the GammaMed unit during the month of May in 2009.

3.2 Transit Time Measurements

For practical reasons (for the purpose of clinical practice), values of the effective transit time were determined to one decimal place, since the source positions at both the GammaMed and microSelectron HDR units can only accept dwell times in increments of 0.1 s.

The effective transit time was determined from the measurements of integrated charge using both the well-type and Farmer-type chambers. The determination used two analysis techniques: the multiple exposure technique and the graphical solution of zero exposure on an exposure versus exposure-time plot.

3.2.1 The Well-type chamber Measurement Technique.

The effective transit times determined with the well-type chamber using both the multiple exposure and graphical techniques are presented in Tables 3.3 (a) and (b) respectively.

Table 3.3 The effective transit times (in seconds) determined by **(a)** the multiple exposure technique and **(b)** the graphical technique for both the GammaMed and microSelectron HDR afterloaders from measurements with the well-type chamber.

(a)

Effective Transit Time (s)				
HDR UNIT	**MAY**	**JUNE**	**JULY**	**AUGUST**
GammaMed	1.5	1.6	1.7	1.7
MicroSelectron	0.4	0.4	0.4	0.4

(b)

Effective Transit Times (s)			
HDR UNIT	**MAY**	**JUNE**	**JULY**
GammaMed	1.5	1.6	1.9
MicroSelectron	0.4	0.4	0.4

A maximum source transit time of 1.9 s was measured with the well-type chamber at the GammaMed unit using the graphical technique. The multiple exposure technique gave a maximum value of 1.7 s. At the microSelectron HDR unit, a constant source transit time of 0.4 s was measured with the well-type chamber using both analysis techniques.

3.2.2 Farmer-type chamber Measurement Technique

The transit times were determined using the jig at four different source-to-chamber distances (SCDs). The transit times determined at the four different measurement distances were then averaged to obtain a mean value for the Farmer-type chamber measurement technique.

Table 3.4 similarly gives the effective transit times determined by the multiple exposure and graphical techniques for measurements with the Farmer-type chamber for both the GammaMed and the microSelectron HDR afterloaders.

Table 3.4 The effective transit times (in seconds) determined by the multiple exposure and graphical techniques for both the GammaMed and microSelectron HDR afterloader from measurements with the Farmer-type chamber.

Analysis Technique	**GammaMed unit**			**MicroSelectron HDR unit**		
	MAY	**JUNE**	**JULY**	**MAY**	**JUNE**	**JULY**
Multiple Exposure	1.4 s	1.5 s	1.2 s	0.3 s	0.4 s	0.4 s
Graphical Solution	1.5 s	1.5 s	1.4 s	0.4 s	0.5 s	0.4 s

A maximum source transit time of 1.5 s was measured with the Farmer-type chamber at the Gammed unit by using both the multiple exposure and graphical techniques. Similarly, at the microSelectron HDR unit, a maximum source transit time of 0.5 s was measured by the graphical technique, whereas by using the multiple exposure technique, a maximum value of 0.4 s was obtained.

The mean values of the effective transit time (averaged over the months of May to August in 2009) for the Gammamed and microSelectron HDR units are given in Tables 3.5 and 3.6 for each measurement technique. Tables 3.5 and 3.6 also give the percentage difference between the mean values of the source transit time for measurements with the well-type and Farmer-type ionization chambers.

Table 3.5 The mean values of the effective transit time determined by **(a)** the multiple exposure technique and **(b)** the graphical technique. The percentage difference between the well-type and Farmer-type chamber measurement technique is given.

(a)

HDR Unit	Mean Values of Transit Time (s)		Percentage Difference (%)
	Well-type chamber	Farmer-type chamber	
GammaMed	1.6±0.1	1.4±0.1	12.5
MicroSelectron	0.4	0.4±0.1	0.0

(b)

HDR Unit	Mean Values of Transit Time (s)		Percentage Difference (%)
	Well-type chamber	Farmer-type chamber	
GammaMed	1.7±0.2	1.5±0.1	11.76
MicroSelectron	0.4	0.4±0.1	0.0

It is clear from Tables 3.3 to 3.5 that the transit time does not depend on the measurement technique, measurement distance, the analysis technique used or the period when it is measured. It does however depend on the type of remote afterloading technology used.

Table 3.6 gives the maximum mean value of the effective transit time averaged over all variables from this study.

Table 3.6 The maximum mean value of effective transit time and its standard deviation for the measurements with the well-type and Farmer-type ionization chambers.

HDR Brachytherapy Unit	Well-type chamber		Farmer-type chamber	
	Maximum mean value of transit time (s)	Standard deviation (s)	Maximum mean value of transit time (s)	Standard deviation (s)
GammaMed	1.7±0.2	0.09	1.5±0.1	0.01
MicroSelectron	0.4	0.0	0.4±0.1	0.01

3.3 Transit Dose Components of the ^{192}Ir HDR Brachytherapy Sources

3.3.1 Different Source Configurations and Source Strengths

Clinically, brachytherapy prescriptions range from 200 cGy per fraction for a high activity source of 10 Ci on delivery to 900 cGy per fraction for a low activity source of 3.2 Ci at replacement. If a source of 8.1 Ci delivers 600 cGy to a prescription point of 1 cm in a total treatment time of 58.9 s with one source position, a source of 3.2 Ci delivering 900 cGy would take 223.6 s, whereas a source of 10 Ci would deliver 200 cGy in 15.9 s.

.

Different Source Configurations

It takes 58.9 s for a source of 8.1 Ci to deliver a prescription dose of 600 cGy to a prescription point of 1 cm for one source dwell position. If the same source delivered 600 cGy to the same prescription point from three different source dwell positions, the total treatment time would be 89.3 s. For a source transit time of 1.7 s, the source would deliver an additional 17.4 cGy to the total prescription dose for one dwell position and 11.4 cGy for three different dwell positions only if they are not interrupted. The relative transit dose would therefore vary with the source dwell time and the source configuration employed. The total integrated relative transit dose would increase with a decrease in source dwell time since the radiation dose delivered at a dwell position varies with the dwell time, but the transit component remains relatively constant.

CHAPTER FOUR - DISCUSSION

Historically users of HDR brachytherapy treatment planning systems do not incorporate the transit time into the computation of patient dose. To ensure safe dose delivery in brachytherapy, accurate quantification of the effective transit time of a HDR brachytherapy unit is necessary in order to compute the total radiation dose given to the treatment volume. A finite transit time increases the radiation dose beyond that due to the programmed source dwell time alone. A maximum mean source transit time of 1.7 s was measured at the GammaMed unit and 0.4 s at the microSelectron HDR unit.

A Nucletron microSelectron HDR unit corrects for source transit time by reducing the programmed dwell time by an amount of up to 0.1 s[4, 7] with a maximum source speed of 500mm/s[18]. At the time of writing this report, no such corrections have been reported for the GammaMed unit. It has also been reported that the transit dose of a microSelectro HDR unit is affected more by the entry/exit component as the inter-dwell component has been accounted by the afterloader itself[7, 18]. This may explain why the transit time of the GammaMed unit is more significant than that of the microselectron HDR unit.

Treatment planning systems usually ignore the transit dose component in the computation of patient dose based on the assumption that clinically significant dose delivery only occurs while the source is stationary and that the dose delivered at a point is proportional to the source dwell time at each dwell position[2]**.** This general assumption cannot always be made because the results of this study show that transit dose depends on a number of factors such as the source strength, the number of treatment fractions, source configuration, number of times that the source enters/exits its dwell position and the type of remote afterloader used.

While some authors and reports such as Goetsch[5], Thomadsen[12] and AAPM TG 41[16] concluded that the transit effect varies with the measurement technique or measurement distance, this study proves otherwise. The slight variation in the values of the effective transit time between the two measurement techniques used (well-type and thimble

ionization chambers) is within the uncertainties of the measurements. These uncertainties include:

- Positional uncertainties or inaccuracies in the measurement distances (SCD) using a calibration jig in the open-air measurement method as the distances are not simple to reproduce accurately from one measurement to another. At 25 cm calibration distance, a 2.0 mm positional error could lead to 1.6% in dose[16]. The uncertainty in the distance error worsens at a very small distance such as 5 cm and requires a larger geometric correction for the size and shape of the thimble chamber[5]. Also, the use of a jig of low density plastic increases room radiation scatter;
- Well-type and Farmer-type chambers response differently to radiation scatter. In addition, the collecting volumes of the two detectors were different. As a result, the two detectors responded differently to the ionization signals measured.

Due to the uncertainties in measurements using an ionization chamber dosimetry system, Thomadsen[12] noted that neither the well-type chamber method nor the open-air geometry technique gives the true transit time, but that any measured 'equivalent' transit time serves as a baseline for changes in the source transit over time.

A multiple exposure technique, which uses different source configurations, was used both for the integrated charge measurements and the transit time determination. Physically, this means that if the dose rate (or reading) for one measurement configuration is different from another with the measurement taken for the same amount time, then there is a transit effect. This study shows that there is a transit effect as the readings were different for the different source configurations. Clinically, this difference means that if a brachytherapy treatment delivery is interrupted, say 'm' times, or the treatment is being delivered in a large number of small fractions with a higher activity source rather than in a single large fraction with a low activity source, then that interruption or fractionation schedule would systematically affect the dosimetry if the transit effect is significant.

There is an increased risk of late tissue effects following the delivery of 'tumour equivalent' HDR doses compared to LDR brachytherapy[4]. To reduce the risk of these late tissue complications, radiobiologists recommend fractionated treatments for HDR brachytherapy[4]. Since source motion is inherent in each HDR treatment cycle, the total transit dose would increase linearly with the number of treatment fractions. For m round trips of the source for the entry to and exit from its dwell position, the transit dose would be m times greater than for a single round trip. Thus when a brachytherapy treatment delivery is interrupted or a fractionated treatment is being considered, corrections for source transit should be taken into account.

CHAPTER FIVE – CONCLUSIONS

In this study, the effective transit times of two HDR brachytherapy units (GammaMed and Nucletron microSelectron HDR) were determined. The transit effect was investigated for two different measurement and analysis techniques, different source configurations and strengths. To ensure safe radiation dose delivery in brachytherapy, it is necessary to determine and compensate for any significant transit time/dose component due to the transit of the radioactive source to its dwell position, between dwell positions and during retraction back into the safe. This study concludes as follows:

1. The effective transit time for the GammaMed unit was determined to be 1.7 s and that of the microSelectron HDR unit was 0.4 s.
2. A finite transit time increases the radiation dose beyond that due to the programmed source dwell time alone. Also, if a higher activity source delivers m irradiation fractions or a treatment delivery is interrupted m times the transit dose would be m times higher.
3. The transit dose depends on the source activity, source configuration, prescription dose, the number of treatment fractions and the type of remote afterloader used. It does not depend on the measurement technique, measurement distance or the analysis technique used for transit time determination.
4. The transit dose would follow an inverse square fall-off with increasing distance.
5. The total radiation dose delivered during each treatment cycle is equal to the static dose plus the transit dose.
6. The significance of the transit dose would increase with a decrease in source dwell time, a higher activity source or an increase in the number of catheters and channels used.

APPENDIX A

SOURCES OF UNCERTAINTIES IN THE MEASUREMENTS

This appendix lists and explains the sources of uncertainties during the measurements using an ionization chamber dosimetry system. These uncertainties usually affect the determination of source strength during the calibration of ^{192}Ir HDR brachytherapy sources[6].

A.1 Uncertainties in Measurements using the Well-type ionization chamber

Although well-type chambers are recommended for the calibration of brachytherapy sources because they are ideally suited for routine clinical calibrations than thimble ionization chambers[19], they exhibit some uncertainties. In the well-type chamber measurements, there are uncertainties that occur due to recombination losses; however, good quality chambers exhibit negligible recombination effects for brachytherapy sources. Other sources of uncertainties are due to the following:

- Well-type chambers designed for HDR sources exhibit heat dependency. The insertion of a very high activity Ir-192 HDR source can cause a temperature increase inside the chamber. Chambers designed with a Styrofoam insert reduce this effect.
- Loss of pressure due to gas leakage affects the sensitivity of high pressure gas (usually argon) filled well type chambers. Chambers that are open to the atmosphere do not require correction for changes in the ambient temperature and pressure.
- Well-type chambers are very sensitive to detect scatter radiation[19]. It is recommended that they should be placed at least 1 m from any scattering surface (walls, ceiling & floor) that might scatter radiation back to the chamber.
- Positional uncertainty, if the source is not positioned at the calibration point of the chamber.

A.2 Uncertainties in Measurements using the Farmer-type ionization chamber

The estimated uncertainty using an ionization chamber based dosimetry system in brachytherapy HDR remote afterloading source calibrations is about 1.5%[6]. These uncertainties are discussed below.

A.2.1 General Sources of Uncertainties

The uncertainties are due to[6]:

- Attenuation of the primary photons by the air between the source and chamber;
- Room scatter; This is due to the scattering of radiation from walls, floor, ceiling, air, jig and nearby objects in the room closed to the measurement set-up.
- Non-uniform electron fluence within the air cavity of the ionization chamber (due to the non-uniform photon fluence over the chamber wall, resulting to a significant variation of the generation of electrons from place to place in the wall).
- Uncollimated brachytherapy sources measured at short distances. At these short distances, air kerma measurements are extremely sensitive to positional uncertainties;
- Recombination losses and current leakage;
- The use of a jig to hold the source and chamber in precise position during calibration unavoidably compromises between the need for mechanical rigidity and the desire to reduce scatter. Both of these issues contribute to a major part to the overall uncertainty.

A.2.2 Uncertainties Due to Measurement Distances

Increasing the distance decreases the uncertainty in the calibration distance and the effect of the finite size of the ionization chamber. However, this improvement results in a reduced signal and an increased relative importance of room and equipment scatter. There are four effects (expressed as a function of distance between the source and the chamber (source-to-chamber distance (SCD)) that contribute to the uncertainties in the calibration of brachytherapy sources using an ionization chamber[6]. These effects are:

- Uncertainty due to the effects of the chamber size. The uncertainty in the non-uniformity correction factor decreases with increasing SCD;

- Scatter, which as a percentage of the total signal increases with increasing SCD;
- Positional uncertainty, which follows the inverse square law and thus decreases with increasing SCD; and
- Leakage current relative to the ionization reading, the effect of which increases with increasing SCD.

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