DETERMINING TRANSIT DOSE FOR THE BEBIG SAGINOVA® HDR Ir-192 STEPPING SOURCE BRACHYTHERAPY UNIT

MILLICENT WANGUI MURIITHI
B.Tech. (TUK)
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DECLARATION

This research project is my original work and has not been presented in any other institution for a degree award or other qualification.

MILLICENT WANGUI MURIITHI

SPPV/05094P/2021

SIGN……..…….. DATE…….

This research project has been submitted with our approval as supervisors:

PROF. JACKSON MAXWELL ODOTE

DEPARTMENT OF TECHNICAL AND APPLIED PHYSICS

THE TECHNICAL UNIVERSITY OF KENYA

SIGN……..…… DATE…….

DR. JOASH ONGORI

DEPARTMENT OF TECHNICAL AND APPLIED PHYSICS

TECHNICAL UNIVERSITY OF KENYA

SIGN……..…… DATE…….

DEDICATION

I dedicate this project to my father, Mr. Geoffrey Muriithi and mother, Mrs. Beatrice Muriithi for being a strong source of inspiration to go on whenever challenges came up. I also dedicate this project to myself, for willing to not give up and mastering all the skills I learnt and obtained during actualization of this research project.

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Last but not least, I acknowledge God for his grace and favor.

ABSTRACT

The Bebig SagiNova® HDR brachytherapy treatment unit implements the TG-43 formalism in calculating radiation dose, which does not account for transit doses during treatment. It is unclear how significant the transit dose is and depending on its magnitude, it may impact the clinical outcome. The goal of this study is to determine the transit dose component for the Bebig SagiNova® HDR brachytherapy unit with an Ir-192 stepping source.

The well-type chamber measurement technique was used to measure charge collected as the Ir-192 source moved from the afterloader. The charge measurements were collected for different source configurations and analyzed using two techniques; the multiple exposure method and the graphical method to determine effective transit time. The overall effective transit time was quantified as the source moved to its first dwell position (entry time), between activated dwell points (interdwell time) and during retraction out of the applicator back into the afterloader (exit time).

The effective transit time of 2.02s was obtained with the multiple exposure method as well as the graphical solution method. The effective transit time was not influenced by the analysis technique. The overall effective transit time for the unit was determined to be about 13.80s and 13.99s using the multiple exposure method and the graphical solution respectively. The significance of the amount of dose during transit is not clear, as it depends on the activity and configuration of the source, prescribed dose and the quantity of treatment fractions used. It is necessary to determine and document transit time and doses for assessing their significance on the delivered dose to help improve the overall efficiency of brachytherapy and patient care.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
Ci	Curie, is an old unit of measurement for radioactivity unit for radioactivity replaced by the Becquerel (Bq). 1Ci = 3.7 × 10^10 Bq
ESTRO	European Society for Therapeutic Radiology and Oncology
Gy	Gray, is the SI unit for absorbed dose. Subunits are mGy and cGy
HDR	High Dose Rate
IAEA	International Atomic Energy Agency
Ir-192	Iridium – 192 radionuclide
KERMA	Kinetic Energy Released in Materials
MeV	Megaelectron Volt, it is a unit of energy
MOH	Ministry of Health
RAKR	Refence Air Kerma Rate
TG-43	Task Group 43
TPS	Treatment planning system
TRAK	Total Reference Air Kerma
QA	Quality Assurance

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

One of the main challenges identified in cancer prevention and control in Kenya is limited access to the necessary services and inefficiently organized cancer management and referral (MOH, 2022). Cancer management refers to a comprehensive strategy aimed at addressing the needs of patients with cancer. It involves a variety of interventions aimed at improving outcome, including prevention, diagnosis, treatment, and supportive care. Typically, a team of healthcare professionals and specialists collaborate to provide individualized care to each patient's specific situation. Holistically, cancer management is a comprehensive, patient-centered approach that strives to provide best possible care and support for cancer patients' step by step process, from intervention after diagnosis to being a survivor or hospice care.

In cancer treatment there are several cancer treatment modalities available, which are chosen based on the type of cancer, staging and location. The patient's overall health and age are taken into consideration, among other variables. Some cancers respond more effectively to a combination of several different treatment modalities, and the decision similarly depends on a range of factors (Mayo Clinic, 2023).

Some of the most common cancer treatment modalities:

- Surgery: This involves surgically extracting the malignant tumor and neighboring tissue, and is often the first treatment option for many types of cancer.
- Chemotherapy: This involves using medication to kill or slow the proliferating cancer cells throughout the body. Chemotherapy may be given orally, intravenously or on the skin surface.

- Immunotherapy: This involves equipping the body's immune system with the capacity to fight cancer cells. The idea is for the immunotherapy drugs to assist the immune system with the natural ability to recognize and destroy cancer cells.
- Hormone therapy: This involves using medication that alter hormone levels for certain hormones that may stimulate the proliferation of cancer cells or by hindering their effects. It is commonly used in the treatment of hormone receptor-positive cancers which rely on hormones to grow and multiply.
- Radiation therapy: This involves using high-energy radiation to eliminate cancer cells or shrink tumors. It may be delivered from an external machine that directs radiation to the tumor from outside the body, or an internal source placed in or next to the tumor what is referred as brachytherapy.

The use of small radioactive sources enclosed in capsules, positioned in or next to the tumor to irradiate malignant tumors or non-malignant lesions, is known as brachytherapy. Brachytherapy is particularly effective in treating cancers that are small in size and localized to particular areas of the body, such as the prostate, cervix, or breast. It may be used to treat early-stage cancers that have not spread beyond the primary site, as well as some advanced-stage cancers in combination with other treatment modalities. This technique is crucial in the treatment of cancers affecting various sites, such as the brain, head and neck, breast, uterine cervix, endometrium, prostate and skin (Nath *et al.*, 1997).

There are different types of brachytherapy treatments such as:

- Intracavitary brachytherapy: This is where sources are positioned near the tumor volume within body cavities.

- Interstitial brachytherapy: This is where the radioactive sources are inserted in the tumor volume. The dosage is administered continuously, through implants either for a short-term or through the lifetime of the source until full decay in permanent implants.
- Intraluminal brachytherapy: This type of brachytherapy involves placing a radioactive source inside a hollow organ, such as the bronchi or oesophagus, for the treatment of cancers in these organs.
- Surface brachytherapy: Surface brachytherapy involves applying a radioactive source directly to the surface of the skin or other body tissues, such as the oral cavity. It is commonly used to treat skin and oral cavity cancers.
- Intraoperative brachytherapy: In this type of brachytherapy, the radioactive source is directly put on the tumor during surgery.
- Intravascular brachytherapy: This type of brachytherapy involves placing a radioactive source inside a blood vessel to treat certain types of cancer that have spread to the blood vessels (IAEA, 2005).

Brachytherapy sources come in different forms, including tiny pellets or seeds, wires, or capsules. The choice of source depends on the type, location, and size of the tumor being treated. Common isotopes used in brachytherapy sources include iodine-125 (I-125), cobalt-60 (Co-60), cesium-137 (Cs-137), palladium-103 (Pd-103), and iridium-192 (Ir-192).

Brachytherapy is a versatile treatment option and can be used for various types of cancer, including prostate, breast, gynecological, and skin cancers. It can be delivered in two main ways: High Dose Rate (HDR) and Low Dose Rate (LDR), each with its own unique benefits and applications. HDR brachytherapy uses a highly radioactive source with high activity, typically Ir-192 or other isotopes with high specific activity. The source is delivered to the treatment site using an afterloader, a

machine that precisely positions and retracts the source. HDR treatments involve short exposure times, usually for a span of a few minutes to less than an hour. The source is temporarily placed near the tumor site, and then removed after the prescribed treatment time.

LDR brachytherapy uses sources with lower specific activity, such as seeds containing isotopes like I-125 or Pd-103. These sources emit a continuous, lower dose rate of radiation. LDR treatments involve continuous, low dose rate irradiation over an extended period, often several days to weeks. The sources are left in place during the entire treatment period.

Ir-192, a radioactive isotope of iridium, is produced through the irradiation of naturally occurring iridium in a nuclear reactor. When iridium-191 captures a neutron, it transforms into iridium-192, which has a half-life of approximately 74 days. As a transition metal belonging to the platinum group, Ir-192 exhibits a 95% probability of undergoing beta decay, resulting in the formation of platinum-192 and the emission of gamma rays. Additionally, there is a 5% probability of decay through electron capture, leading to the formation of osmium-192 (see Figure 1.1).

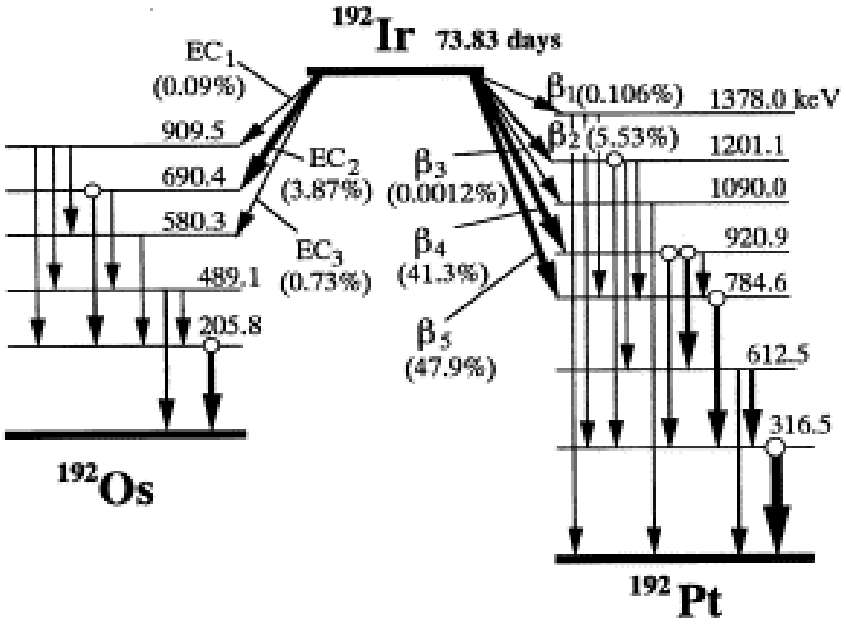


Figure 1.1: Ir-192 decay scheme (Oncology Medical Physics, 2018)

During beta decay, Ir-192 emits high-energy beta particles (electrons) with a peak energy of 0.606 MeV. Furthermore, it releases gamma radiation (photons) characterized by energies of 0.316 MeV and 0.468 MeV. These properties make Ir-192 highly valuable in diverse applications across industrial, medical, and research settings (Ahmad, 2013). One significant application of Ir-192 is in brachytherapy, where it is often enclosed within small, sealed sources. By emitting high-energy beta particles and gamma radiation, Ir-192 effectively targets and destroys cancer cells by causing damage to their deoxyribonucleic acid (DNA).

Regarding the process of loading the source into the patient, it may be done using either of these techniques:

- The "hot loading" technique which involves pre-loading of an applicator with radioactive sources before its placement into the patient.
- The "afterloading" technique which entails first placing the applicator into the patient, followed subsequently loading of radioactive sources. This loading can be done manually (manual afterloading) or using a machine (automatic remote afterloading) (IAEA, 2005).

Using a HDR brachytherapy stepping source using the automatic remote afterloading (computer-controlled delivery) of radiation sources technique is a prevalent approach (Glasgow *et al*., 1993). After the applicators have been inserted, the dose rate to specific areas such as the bladder, sigmoid, rectum, and prescription point, is determined through the use of orthogonal radiographs. Orthogonal radiographs are two X-ray images taken at right angles to each other, which provide a clear view of the position and location of the reconstructed applicators in relation to the surrounding anatomy (see Figure 1.2). These radiographs are used to visualize the dose distribution and make sure that the prescribed dose is delivered efficiently to the target area and radiation exposure to adjacent healthy tissue is optimized (see Figure 1.3). The calculated dose rate to all

our areas of interest helps to determine the appropriate treatment time for the brachytherapy procedure.

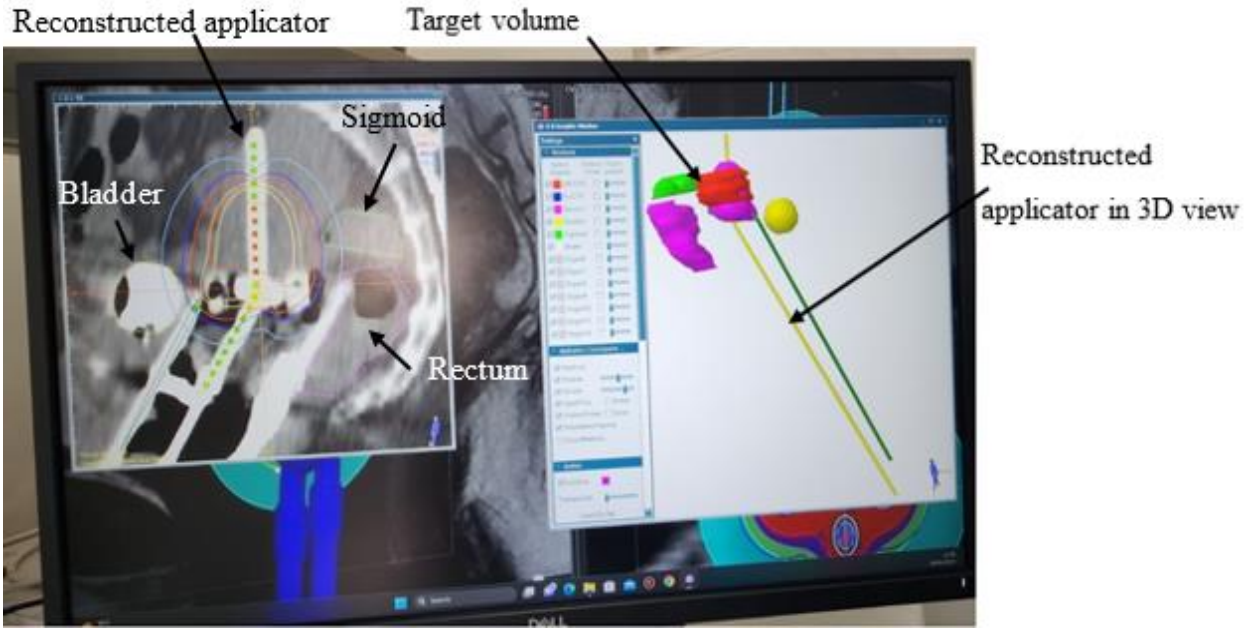


Figure 1.2: Sample image showing a clear view of the position and location of reconstructed applicators in relation to the surrounding anatomy.

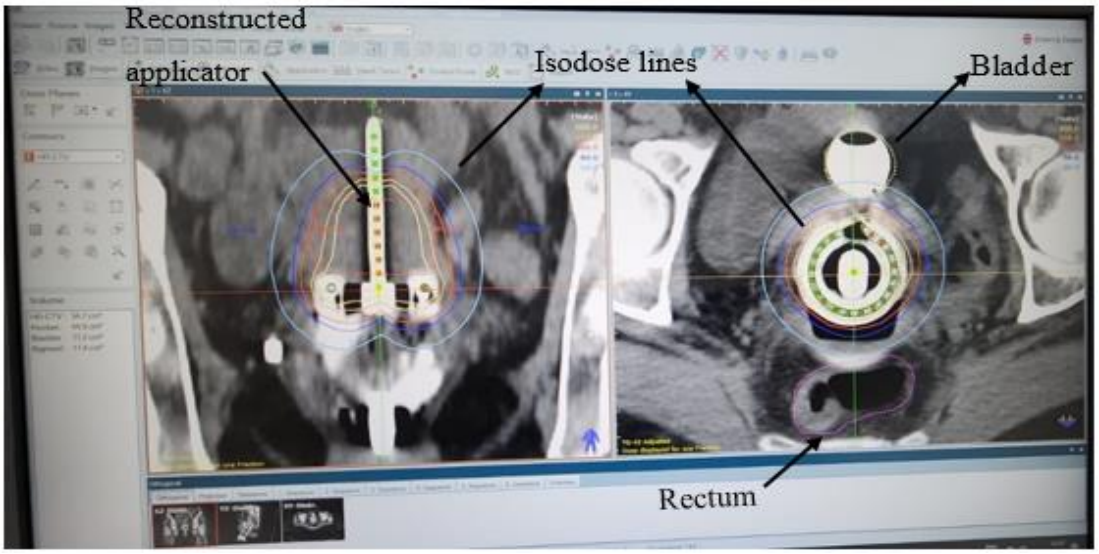


Figure 1.3: An image showing the dose distribution using isodose lines around the target volume during optimization process on orthogonal radiographs.

In single stepping HDR brachytherapy, the source is moved to a singular position at a time, and the radiation is delivered in single steps. After the radiation is delivered at one position, the source moves to the next position, and the process recurs until the entire treatment is complete. The source follows a path along the applicators, dwelling at predetermined positions, known as dwell points, for specified amount of time called dwell time (Nag, 2004) as shown in Figure 1.4. Once the tracking process is complete, the overall average dose distribution is achieved, ensuring that the radiation dose is administered precisely and safely.

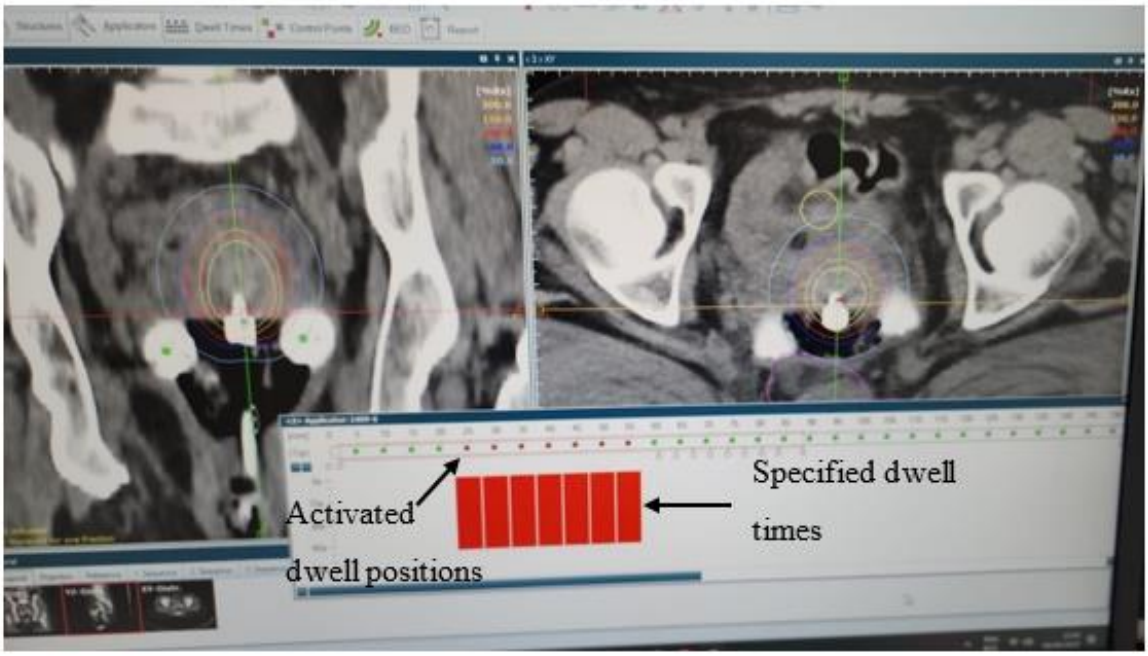


Figure 1.4: Sample image showing activated predetermined dwell positions for specified dwell times.

1.2 STATEMENT OF THE PROBLEM

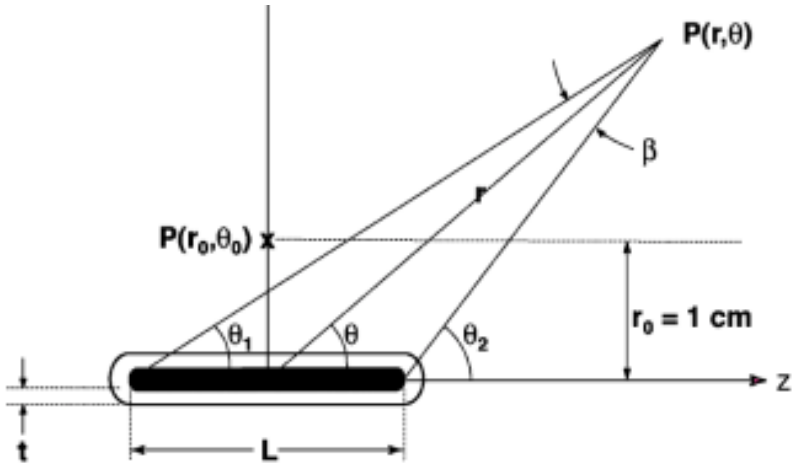
The American Association of Physicist in Medicine Task Group-43 (AAPM TG-43) is a report that provides a set of guidelines for calculating radiation dose in brachytherapy. The AAPM TG-43 protocol provides standardized dosimetry variables for brachytherapy sources. The AAMP

TG-43 report is a widely used dosimetry protocol for brachytherapy treatments by radiation oncologists, medical physicists, and dosimetrists in the planning and administering of brachytherapy treatments. The report provides a standardized framework for calculating radiation dose, which helps to ensure consistency and accuracy in treatment planning and delivery. The report was published first in 1995 (Nath *et al*., 1995) and has been updated several times since then.

The TG-43 protocol is based on a set of mathematical formulas that describe the radiation dose distribution around the brachytherapy source in water. These formulas take into account parameters such as the energy and geometry of the source, distance between radiation source and the target area, and the attenuation of the radiation as it passes through the water.

The report includes information on the properties of different types of radioactive sources used in brachytherapy, as well as guidance on how to take into account the influence of source anisotropy, tissue heterogeneity, and other factors that can affect the accuracy of radiation dose calculations. The TG-43 report provides a framework for calculating the radiation dose delivered to the tumor and normal tissues surrounding it during brachytherapy.

It outlines a standardized method for calculating dose distribution around a point source of radiation, taking into account variables such as the radial dose function, the anisotropy function, and the dose rate constant, to calculate the radiation dose delivered to the patient (see Figure 1.5). The radial dose function describes how the radiation dose decreases as the distance from the source increases, while the anisotropy function describes how the radiation dose varies with angle around the source. The dose rate constant is a measure of the strength of the radiation source and is used to calculate the radiation dose at a specific distance from the source.



where; r **is the distance from the center of the active source to the point of interest** $p(r,\theta)$

r_θ **is the reference distance which is specified to be 1cm in this protocol**

θ **is the polar angle specifying the point of interest** $p(r,\theta)$**, relative to the source longitudinal axis**

θ_0 **is the reference angle which defines the source transverse plane specified to be** 90°

Figure 1.5: Coordinate system used for brachytherapy dosimetry calculations (Rivard *et al*., 2004)

The purpose of the TG-43 report is to assure that the radiation dose delivered during brachytherapy is accurate and consistent across different institutions and treatment centers. By using standardized methods for calculating radiation doses, clinicians can ensure that the desired therapeutic effect is attained while minimizing the risk of side effects from the treatment. The TG-43 protocol is widely used in brachytherapy treatments for a variety of cancers, with prostate cancer, cervical cancer, and breast cancer being among the most common. It is also used to

develop new brachytherapy sources and in the evaluating the existing sources which ensures their safety and efficacy.

Overall, the AAPM TG-43 report has been widely adopted and has become the standard reference for brachytherapy dosimetry. It is an important resource for clinicians and medical physicists involved in the planning and administering of brachytherapy treatments. It provides a standardized approach for the calculation of radiation doses that is widely recognized and used in the field of radiation oncology (Mehdi Zehtabian *et al.*, 2012).

However, the TG-43 report does not account for transit doses during treatment. The transit dose is mainly due to the radiation emitted by the source as it moves to its first dwell position (entry dose), between activated dwell points (interdwell doses) and during retraction out of the applicator back into the afterloader (exit dose) through the patient's tissues during treatment (Ade, 2009). In consequence, once the radiation source has left its capsule in the afterloader and because it constantly emits radiation, it indicates that there is possibility of an increment of radiation dose; the dose administered to the target volume may exceed the initially calculated and optimized dose from the treatment planning, and in certain situations, perhaps dose to the normal organs under some circumstances.

1.3 MAIN OBJECTIVE

The goal of this study is to determine the transit dose component for the SagiNova® HDR Ir-192 stepping source brachytherapy unit. This will involve quantifying the overall effective transit dose and determining whether it is significant or negligible.

1.4 SPECIFIC OBJECTIVES

Specifically, the research aims to:

i. Determine the effective transit time for the SagiNova® Ir-192 HDR afterloader.

ii. Quantify the overall effective transit time component for the Ir-192 HDR brachytherapy stepping source unit.

iii. Evaluate the significance of the transit dose contribution by comparing it to the calculated dose obtained from the TG-43 computation technique for various configurations of sources and their respective strengths.

1.5 HYPOTHESIS

It is assumed that the transit dose contributes to a significant increase in the absorbed dose to the treatment volume and perhaps to the normal organs during radiation therapy. Specifically, it is anticipated that:

i. The transit dose will have a measurable impact on patient dosimetry, with higher transit doses leading to greater increases in the dose absorbed by the treatment volume and the normal organs.

ii. The significance of the transit dose will vary depending on factors such as the length and number of applicators used, the number of dwell points activated to cover the treatment volume and the source strength.

iii. The transit dose will have a clinical impact on treatment outcomes and patient side effects, where higher transit doses may lead to increased risk of complications and poorer treatment outcomes.

iv. Based on the findings, recommendations will be made as to whether compensation is required.

1.6 JUSTIFICATION OF THE STUDY

The SagiNova® HDR brachytherapy treatment unit using an iridium-192 source implements the TG-43 formalism in calculating radiation dose and is used for various treatments. It is not clear how significant the quantity of the dose during transit times from entry to exit point, but depending on its magnitude, it may impact the clinical outcome. It is therefore necessary to determine and document transit doses for assessing their impact on the patient to help improve the overall efficiency of brachytherapy and patient care.

CHAPTER TWO

LITERATURE REVIEW

Over the years, several people have contributed to determining transit time and dose for various brachytherapy units all in an attempt to improve the efficiency of brachytherapy treatments. Just as they have used different techniques to achieve this, they have also proposed a range of recommendations.

Bastin *et al*. (1992) outlines a research endeavor that directly quantified the transit dose generated by a HDR brachytherapy source and evaluated its clinical implications (Bastin *et al*., 1992). The investigation involved the measurement of doses resulting as the Ir-192 source moved during HDR afterloading, using thermoluminescent dosimeter rods that were calibrated. The transit dose was assessed at distances ranging from 0.5 to 4.0 centimeters from an endobronchial applicator, utilizing a Lucite phantom designed to accommodate $1x1x6$ millimeter thermoluminescent rods. Additionally, they conducted measurements of surface transit dose using esophageal and endobronchial catheters, a gynecologic tandem, and an interstitial needle.

The thermoluminescent rods displayed no reactivity when exposed to the 4MV and Ir-192 spectrum (with a fluence of 427nC/Gy), with the dose spanning from 2 to 300 cGy. The transit dose measured 0.31 cGy at 0.5 centimeter from the endobronchial catheter and exhibited a decrease with greater separation according to the inverse square law. Transit doses ranged from 0.38 cGy to 1.03 cGy on the surfaces for the esophageal and the endobronchial catheter, respectively. The velocity of the radiation source relied on interdwell distances, spanning from 220 to 452 mm/s.

Employing the dynamic point approximation, they came up with a numerical algorithm to compute the cumulative transit dose for a dynamically moving high dose rate source. The algorithm's projections indicated that overall transit doses relied on factors such as source velocity, number of

treatment sessions, and source activity. Similarly, surface transit doses were influenced by applicator diameter, as well as the material and thickness of the applicator wall. The transit doses remained under 100 cGy within or near the targeted treatment area. However, under specific conditions involving a high number of treatment sessions and a source with elevated activity, they could potentially reach 200 cGy. Employing the linear quadratic model, they postulated that the unaccounted dose resulting from treatment planning systems' assumptions of negligible transit doses might elevate the risk of delayed tissue complications for the patient. They recommended incorporating the total transit dose into the calculation of isodose distributions to improve the safety and precision of HDR brachytherapy. They further emphasized the importance of documenting significant transit doses to the tissues surrounding the treatment zone.

Wong *et al*. (2001) research focused on examining the influence of transit dose within the target volume during HDR brachytherapy, employing a single stepping source (Wong *et al*., 2001). They opted for a video-based approach to scrutinize the entry, exit, and interdwell transit speeds of the source, considering various path lengths and step sizes ranging from 2.5 to 995 mm. The recorded transit speeds averaged at 54, 72, 233, 385, and 467 mm/s, corresponding to traveled distances of 2.5, 5.0, 10.0, 230, and 955 mm, respectively. Their findings highlighted that the transit speed exhibited variation based on both the step size and path length. Additionally, they observed that the manufacturer of the brachytherapy unit they employed made efforts to counteract the effects of interdwell transit dose by adjusting the true dwell time of the source.

A well-type chamber was also used to measure the dose disparities between static dose and the combined static with transit doses. In the measurements, they activated lengths of 20 and 40mm on a single catheter using varying dwell times of 0.5, 1.2 and 5s along varying step sizes of 2.5, 5 and 10mm. They found that majority of dose differences between the two were within 2%.

They found that source transit could increase doses to as high as 24.9% for the situation where they used 0.5s dwell time, 10mm step size and 20mm active length.

In conclusion, entrance and exit source movements were found to have a greater impact on the dose difference than interdwell movement.

In this study by Sahoo (2001), the transit time for the Ir-192 source within a Nucletron Micro-Selectron HDR brachytherapy unit was evaluated (Sahoo, 2001). This assessment was carried out using a well-type ionization chamber coupled with an electrometer. The evaluation involved assessment of the electrical charge produced when the source dwelled at a point within an endobronchial catheter inserted into the chamber. This measurement was also conducted during the source's transit from another position, ranging from 0.5 to 10 centimeters away.

To analyze the data, he employed linear regression analysis to establish a correlation between the measured charge and dwell time. The transit time between interdwell positions was calculated by dividing the charge intercept by the slope of the resulting regression line. The effective transit time, cumulative of both interdwell position transit time and the dwell time error of the after-loading unit, was identified as 0.03 seconds for a 0.5 centimeter separation between dwell positions, and 0.45 seconds for a 10 centimeter separation between two dwell positions. He determined that, on average, it took the source 0.022 seconds to travel 1 cm between two dwell positions, equivalent to an average speed of 45.5 cm/s.

In conclusion, the researcher recommended that, for any remote after-loading HDR brachytherapy source, this simple procedure could be employed consistently for quality assurance checks to assess the interdwell position transit time.

In their study, Supe *et al*. (2007), the goal was to quantify the transit time between two dwell positions of a GammaMed-Plus Remote Afterloading HDR Brachytherapy Source (Supe *et al*.,

2007). They implemented a methodology that involved employing a well-type ionization chamber in conjunction with a precise electrometer to assess the charge produced while the Ir-192 source moved from the brachytherapy unit within an interstitial needle.

The charge readings were taken while the source dwelled at two positions, X_1 farthest from the afterloader, and X_2, nearest to the afterloader, along the interstitial needle. The first reading, $q_1$was obtained at point X_1 with source dwelling for time t_1. They then obtained 6 readings for charge q_2 when the source was at point X_1 with source dwelling for time t_1 before moving to X_2 with source dwelling for time t_2 of 5, 10, 15, 20, 25 and 30 s. The net charge, q_n generated as the source transited from X_1 to X_2 as well as during its dwell at X_2 was calculated from;

$$q_n = q_2 - q_1. \quad \text{.....} \quad 2.1$$

The methodology as outlined in (Sahoo, 2001) was used to ascertain the effective transit time and effective speed. They did a linear regression analysis of q_n in relation to t_2 to express q_n as;

$$q_n = I.t_2 + q_0. \quad \text{.....} \quad 2.2$$

Here I is the slope of linear fit representing charge per unit time or current, and q_0 is the intercept of the charge axis. The value q_0 is the charge generated during source transit between two dwell positions. They quantified the effect of these factors by an effective transit time, $t_{eff.tr}$which was quantified using the equation;

$$t_{eff.tr} = \frac{q_0}{I}. \quad \text{.....} \quad 2.3$$

The readings for q_n were made at two source locations X_1 and X_2 for interdwell distances ranging from 1 to 10 cm. Transit times were determined for varying dwell time values, t_1 (5, 10,15 and 20 s) at point X_1. Using relative sensitivity values for different dwell positions within the ionization chamber, corrections were made. The effective transit times for interdwell separations of 1, 2, 4, 6, 8, and 10 cm were determined to be 0.129, 0.182, 0.301, 0.402, 0.701, and 0.993 seconds,

respectively. Supe *et al*. (2007) did not quantify the transit dose component or assess its clinical significance. In their conclusion, they indicate that the results were not purposed to be used clinically due to uncertainties from measurement errors.

Using this study, Ade (2009) determined the magnitude of the transit dose component for two Ir-192 HDR brachytherapy units (GammaMed and Nucletron MicroSelectron HDR afterloaders), using two measurement techniques and assessed its dosimetric significance (Ade, 2009). He collected data for different source activities over a four month period using two ionization chamber dosimetry systems (Farmer type ionization chambers and well-type). Both the free in-air and well-type chamber measurement methods were employed to quantify the charge produced as the Ir-192 source traveled from the afterloaders using single catheters measuring 120 cm in length.

He incorporated varying source configurations and source transfer mechanism to collect integrated charge readings. The first was a single exposure M_s made for a set source dwell time, the source moved to the dwell position, dwelled for a set source dwell time, t and moved out of the catheter. For the second configuration, a 'multiple exposure' M_m made for the same dwell time, but split into short exposures m. The source travelled in and out of the catheter three times but moved to different dwelling points. For the three dwell positions, the source moved to the furthest position and stepped backwards to the final position with an interdwell distance of 10mm. For the third configuration, he did independent measurements at a single position. In all the situations the electrometer readings were taken when the transfers were complete.

Two analysis techniques were used to determine transit time; the multiple exposure technique and the graphical solution of zero exposure. The multiple exposure technique used charge from the single exposure and the multiple exposure, where the effective transit time, $t_{eff.tr}$ was quantified by;

$$t_{eff.tr} = \frac{(M_m - M_s)t}{(mM_s - M_m)}. \quad \text{..... 2.4}$$

The graphical solution of zero exposure involved utilizing multiple charge readings taken at various intervals within the units. Using measurements for each unit transit time was obtained by linear regression and extrapolation. He derived the transit dose, from respective values of transit time for different source strengths, dwell time, prescription dose and different source configurations used.

He recorded a maximum transit time of 1.7 seconds for the GammaMed unit and 0.4 seconds for the MicroSelectron unit. It was observed that the transit dose was dependent on factors such as source activity, source arrangement, number of treatment sessions, prescribed dose, and the specific type of remote afterloader employed. Notably, it was found that the transit dose was independent of the measurement method, measurement distance, or the analytical approach applied in determining transit time.

In his final remarks, Ade (2009) noted that a measurable transit time resulted in an increase of the radiation dose beyond what was expected from the set source dwell time alone. The importance of the transit dose would amplify with a reduction in source dwell time or the use of a more active source. The study showed that when the radiation source moved, it affected the measurements differently depending on how the source was set up. Thus, he concluded that when interruptions occur in the delivery of brachytherapy treatment or when considering fractionated treatments, adjustments for source transit should be factored in.

In their study, Palmer & Mzenda, (2009) undertook a thorough characterization of the Eckert & Ziegler HDR brachytherapy treatment unit with an Ir-192 source (Palmer & Mzenda, 2009). They designed a comprehensive commissioning program, encompassing checks on the absolute dosimetry of the source and vital parameters such as source positioning, dwell timing and transit

doses. Their methodology incorporated measurements using a Well-type chamber, along with techniques like autoradiography and video camera analysis. The absolute dosimetry was validated by national measurement standards laboratory in the UK and compared against measurements based on calibrations by the national metrology institute in Germany, the supplied source certificate, and an unbiased evaluation by a visiting center in the UK. Additionally, they assessed how effective the Krieger dosimetry phantom could be.

The authors advise facilities using this system to carefully consider the correction method used for transit doses. It's important to note that this method does not account for the initial and final transit doses. The findings of this study revealed that unadjusted transit doses may contribute to slight discrepancies in the administered dosage at the initial dwelling point, with a maximum deviation of up to 2.5 cGy at 2 cm or 5.6 cGy at 1 cm from a 10 Ci source. However, the adjustment of transit dose for subsequent dwells demonstrated an accuracy within 0.2 cGy. Based on these outcomes, the authors concluded that the unit has demonstrated reliable mechanical performance, consistent accuracy in source positioning, and dependable dwell timing. Its overall operational performance aligns with other high dose rate equipment currently available. Therefore, when considering the aforementioned recommendations, the unit is deemed capable of administering brachytherapy treatments of high quality.

Finally, Kanani *et al*. (2018) in their study had the objective to evaluate the adjusted source transit time of the SagiNova® HDR afterloader unit independently, without relying on a video camera or stopwatch (Kanani *et al*., 2018). For each HDR afterloader, it is advisable to perform unbiased verification of transit time before any treatment, and Kanani *et al*. (2018) observed that previous reports have utilized video cameras and/or stopwatches for this purpose. To assess the SagiNova® HDR afterloader unit, the researchers employed a radiometric method using a Co-60 source. They

used a well-type ionization chamber and an electrometer to take measurements. Ensuring precise positioning of the source for maximum response, they employed a 30 cm plastic needle and a 100 cm transfer tube. Treatment plans were generated to expose the well-type chamber to radiation with dwell times ranging from 3 to 120s. Each measurement was repeated three times. After being adjusted by the afterloader software, the transit time was evaluated using the ESTRO-recommended approach for obtaining transit time correction factors and as well as another strategy established for teletherapy sources. They compared the results acquired from both strategies.

The study revealed that, for the specific setup employed, the transit time was determined to be 0.7s using both methods. From ESTRO transit time was corrected with 0.93 a mean factor, with a range of 0.88 to 0.99 for dwell times ranging from 3 to 120 s. Their study demonstrated a precise dosimetry-based approach for measuring source transit time during the commissioning phase of high dose rate brachytherapy afterloaders. The method employed was practical and utilized standard equipment that is readily available. The research demonstrated the consistency of results obtained through the two radiometric methods to determine transit time for the source.

The findings indicated that the adjustment performed by the afterloader software does not entirely account for this effect, resulting in slightly increased irradiation times. In their conclusion they emphasize the need to consider the transit time and its impact on dosimetry, even with the software correction in place.

CHAPTER THREE

METHODOLOGY

In this particular chapter, the materials used, site of the study, experimental setup for charge measurements and the different source configurations using the ionization chamber will be briefly discussed.

3.1 MATERIALS

3.1.1 REMOTE AFTERLOADING EQUIPMENT

For generating dwelling time and position plans the Sagiplan 2.2 version was used on the treatment planning system (TPS) located in the planning room. The SagiNova® HDR brachytherapy unit that employs Ir-192 source was utilized to deliver doses. It is located in the brachytherapy bunker as shown in Figure 3.1 with a control room outside the bunker as shown in Figure 3.2.

Figure 3.1: SagiNova® HDR brachytherapy unit.

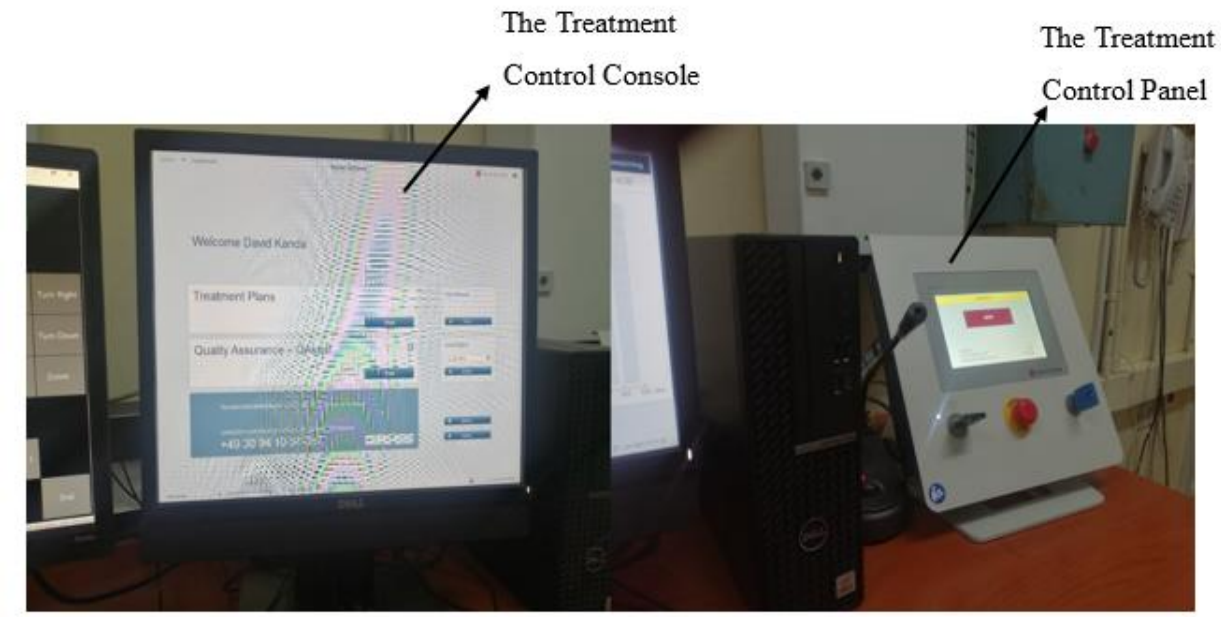


Figure 3.2: The HDR brachytherapy afterloader Treatment Control Console and Treatment Control Panel in the control room.

3.1.2 DOSIMETRY EQUIPMENT

Charge measurements were collected using a well-type ionization chamber. It is the recommended measurement technique by the (IAEA, 2002) as a method for the calibration of Ir-192 when used as a brachytherapy source. This was achieved by utilizing the Standard Imaging HDR 1000 Plus brachytherapy well-type ionization chamber, hereafter referred to as the ionization chamber, which is appropriate for measuring source strength of various types of brachytherapy sources, and the Standard Imaging CDX 2000B electrometer, a lightweight and stable device specifically designed for precise High Dose Rate (HDR) brachytherapy calibrations (see Figure 3.3).

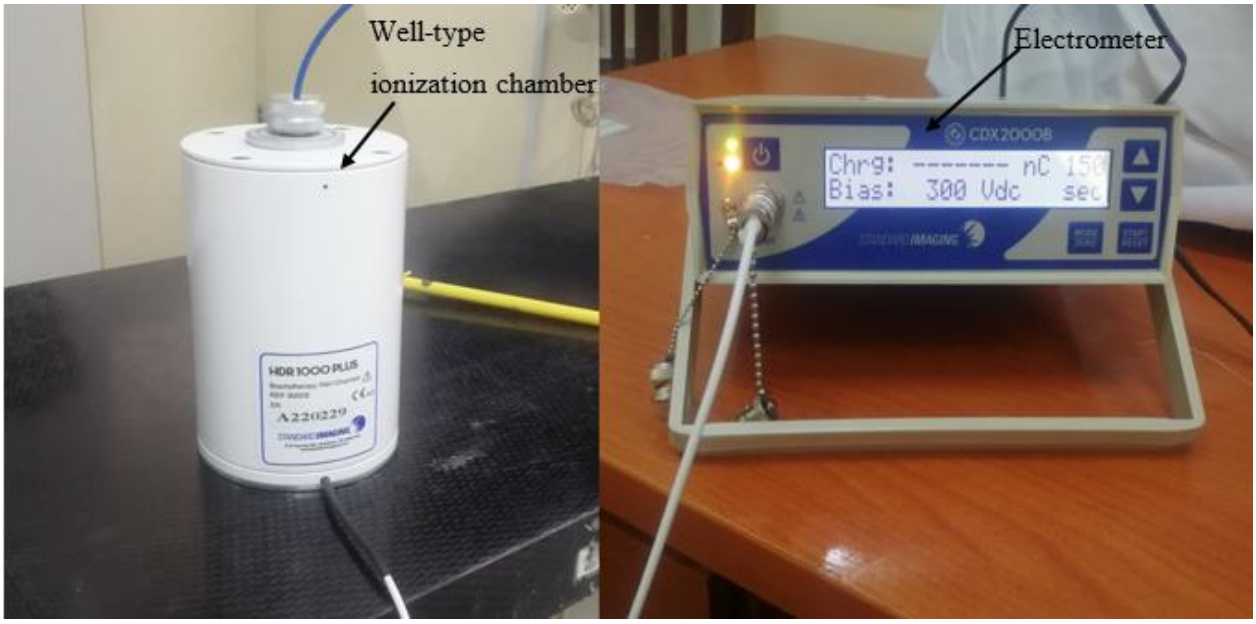


Figure 3.3: The Standard Imaging HDR 1000 Plus brachytherapy well-type ionization chamber and the CDX 2000B Standard Imaging electrometer.

3.2 SITE OF STUDY

The research took place in a clinical setting. The SagiNova® HDR brachytherapy unit is utilized at this facility for brachytherapy purposes. The equipment mentioned was readily available; necessary request and arrangements were made to access them.

3.3 EXPERIMENTAL SETUP FOR CHARGE MEASUREMENTS USING THE IONIZATION CHAMBER

The ionization chamber measurement method which is recommended as an efficient method for calibrating Ir-192 brachytherapy sources was used (IAEA, 2002). In this set up, the source was accurately placed at the reference position of the chamber since the position in the chamber is a factor to the charge reading. For measurements taken at a distance from this position within the ionization chamber corrections were made using relative sensitivity values.

The electrometer was set in the control room and the ionization chamber was set in the treatment bunker next to the afterloader. The Ir-192 radioactive source moved from the afterloader to the measurement dwell points through a single transfer tube (100cm) and an intracavitary applicator (see Figure 3.4). The chamber was placed at least 1m away from walls, ceilings and a reasonable distance from the floor which could cause scatter to avoid backscatter radiation to the chamber as shown in Figure 3.5.

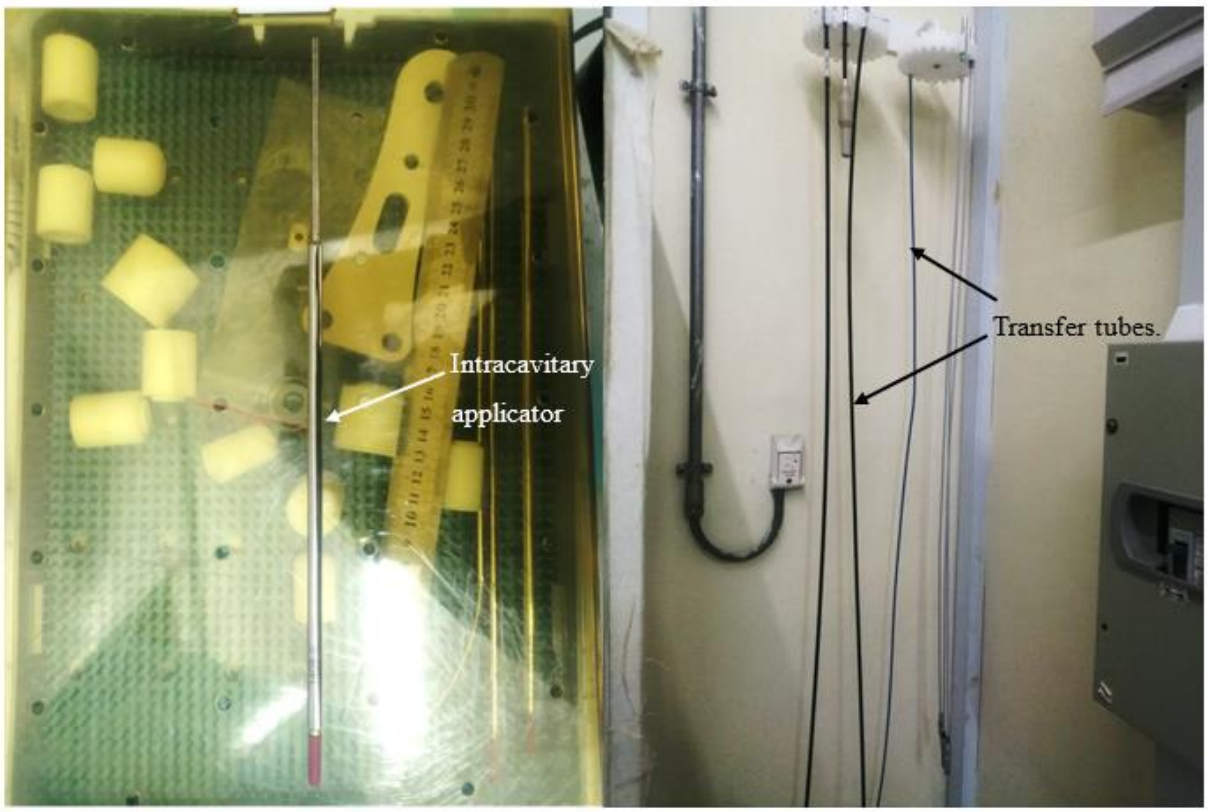


Figure 3.4: An intracavitary applicator and transfer tubes.

Figure 3.5: The measurement set up in the bunker.

3.4 EXPERIMENTAL SOURCE CONFIGURATIONS FOR CHARGE MEASUREMENTS

The charge measurements were collected for different source configurations. The following three source configurations were used:

i. A single exposure for the source E_s , for a predetermined dwelling time

ii. Multiple exposures for the source E_m , for a similar dwelling time but divided into several short exposures

iii. Multiple independent transfers for the source with a single transfer to the respective dwell position

All singular readings were taken at the reference position for the chamber or at multiple dwell positions with the reference position included for the multiple exposures. For the single exposure, the source travelled to the reference position in the applicator, dwelled for 135s and travelled back to the afterloader one time only as illustrated in Figure 3.6.

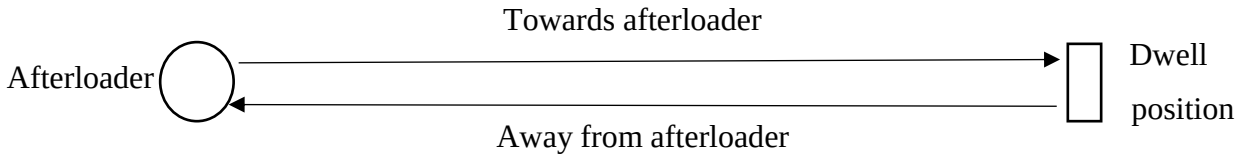


Figure 3.6: The source moves out of the afterloader to the reference position for a given dwell time after which it withdraws into the afterloader.

For multiple exposures, the measurements were read at multiple dwell positions. The source moved to the position furthest from the afterloader and stepped backwards through the programmed positions and back into the afterloader as illustrated in Figure 3.7. For the multiple exposure technique the source dwelled at three positions within the applicator for a dwelling time of 45s each and a stepping interval of 5 mm was used.

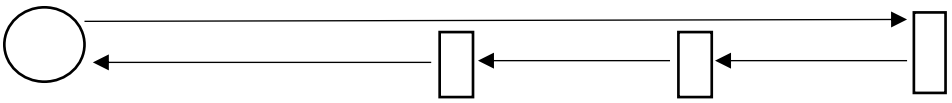


Figure 3.7: The source moves out of the afterloader to the furthest dwell position and the steps back at intervals then withdraws into the afterloader.

For the multiple independent source transfers with a single transfer to a single dwell position, the source was to travel into the applicator, dwell for 45s and out of the applicator back into the afterloader, three times to three different positions as visualized in Figure 3.8.

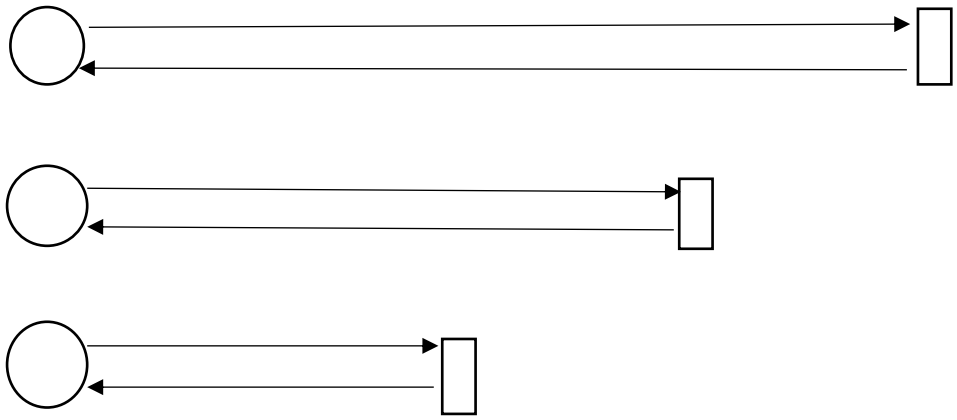


Figure 3.8: Multiple independent source transfers with a single transfer at different dwelling positions. The source travels to the dwell positions and withdraws into the afterloader.

The reading was obtained as an integrated reading in the different configurations, when the transfers were complete with the source retracted back to the afterloader.

3.5 STATISTICAL ANALYSIS OF DATA FOR TRANSIT TIME DETERMINATION

The charge measurements collected were analyzed using two methods namely; the multiple exposure method and the graphical method in order to determine effective source transit time which is the transit time between dwell points (interdwell). The methods are briefly discussed below.

First, in the multiple exposure method, two readings of integrated charge were analyzed and the effective source transit time is given by:

$$t_{eff.tr} = \frac{(E_m - E_s)t}{(mE_s - E_m)}. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3.1$$

Here, the single exposure, E_s was made for a dwell time, t of 135 s, and the multiple exposure, E_m made for the same 135 s, but split into 'm' short exposures of 45s each. m was three for the SagiNova® HDR brachytherapy unit with measurements taken at three different source positions.

Second, a graphical method was also used to determine effective transit time. Using time intervals of 15s, eleven measurement readings for charge were taken for the SagiNova® HDR unit as presented in Table 4.1. These measurements were subjected to linear regression and extrapolation to deduce the transit time for zero exposure as shown in Figure 4.3.

The overall effective transit time component for the brachytherapy unit is a summation of the effective transit time (interdwell transit time) with the entry and exit transit time. To quantify the overall effective transit time component for the unit, the effective transit time, entry and exit transit time will be summed. Note that for the SagiNova® HDR unit it is possible to directly extract the entry and exit transit time, since the system reports the time after a plan delivery is complete (see Figure 4.4)

3.6 TRANSIT DOSE CALCULATION

Using relative values of the deduced transit time, the transit dose element for the Ir-192 was obtained using various source strengths, prescribed dose, dwelling time and different configurations. By comparing how much the transit dose element has contributed towards the dose in relation to the calculated dose by the TPS the significance of was evaluated.

CHAPTER 4

RESULTS AND DISCUSSION

Data yielded from materials and techniques outlined in Chapter 3 is presented and discussed in this present chapter.

4.1 SENSITIVITY OF THE IONIZATION CHAMBER

The ionization chamber's response varies with position, in the chamber. The point of maximum sensitivity, also known as the "sweet spot" or reference position, is a position within the chamber where it exhibits its highest response to radiation. The sensitivity of the chamber in relation to the source position in the transfer tube must be checked to identify the point of maximum sensitivity. The value of current, I_n for different positions of the source along the Quality Assurance (QA) transfer tube, inside the ionization chamber (see Figure 4.1), with step size of 5mm were obtained and the sensitivity was evaluated using:

$$S_n = \frac{I_n}{I_0}, \quad \text{.....4.1}$$

where, I_0 is the peak current from the measured charge for the different dwell positions.

Figure 4.1: Dwell position sensitivity measurements setup.

Table 4.1: Electrometer readings for different positions of the source within the ionization chamber

Position (mm)	**Electrometer Reading (I_n) (nA)**	**Peak Reading ($I_{o)}$ (nA)**	**Sensitivity (S_n)**
20	55.744	59.168	0.942
25	56.857	59.168	0.961
30	57.770	59.168	0.976
35	58.495	59.168	0.989
40	58.933	59.168	0.996
45	**59.168**	**59.168**	**1**
50	59.164	59.168	0.999
55	59.047	59.168	0.998
60	58.620	59.168	0.991
65	57.960	59.168	0.980
70	57.245	59.168	0.967

From Table 4.1 and the graph shown in Figure 4.2, a maximum sensitivity of 1 was achieved at dwell position 45 mm from first active point of 20mm in the quality assurance (QA) transfer tube connected.

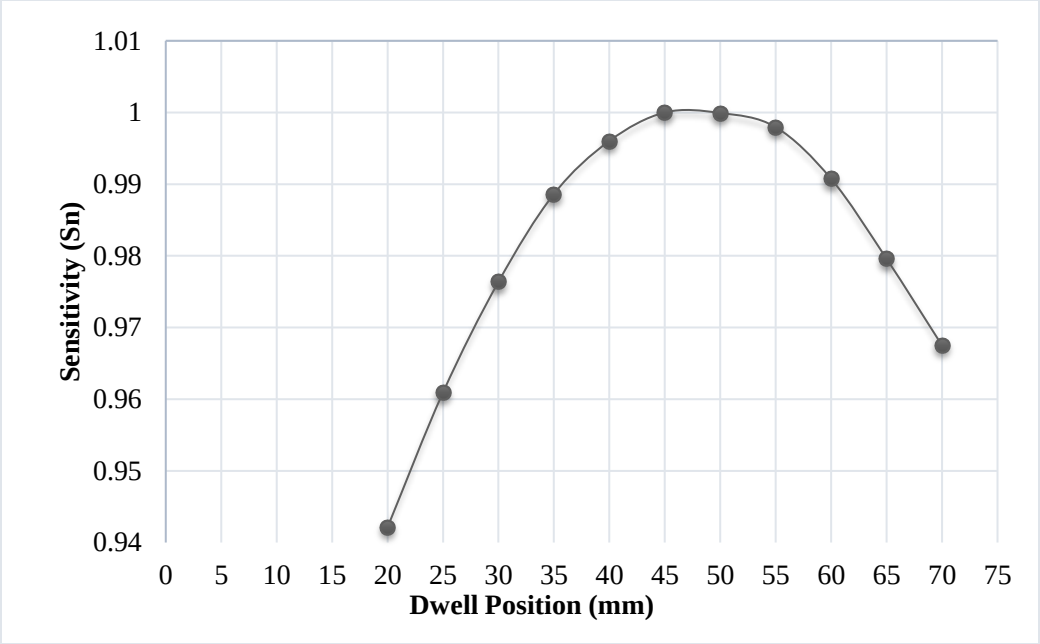


Figure 4.2: Sensitivity curve.

4.2 INTEGRATED CHARGE MEASUREMENTS

Likewise, as discussed in Chapter 3 Subsection 3.4, different configurations were used to obtain the charge measurements. Table 4.2 presents outcomes for the charge measurements from the multiple exposure method.

Table 4.2: The findings from the charge measurements conducted using the multiple exposure method.

	E_s (nC)	**E_m (nC)**
Reading 1	7448.80	7669.10
Reading 2	7449.40	7670.30
Reading 3	7449.80	7668.70
Average	**7449.30**	**7669.37**

Furthermore, measurements for integrated charge readings were collected at the reference position of the chamber for varying durations (see Table 4.3). The dwelling time ranged from 15s to 165 s. These measurements were subjected to linear regression and extrapolation to determine the transit time for zero exposure as intercept on the time axis (see Figure 4.3).

Table 4.3: Measurements for integrated charge readings collected at the reference position for different amounts of time.

Time (s)	**Charge (nC)**
15	780.7
30	1633.7
45	2500.4
60	3377.5
75	4202.8
90	5149.8
105	6097.7
120	6924.6
135	7804.3
150	8674.5
165	9476.0

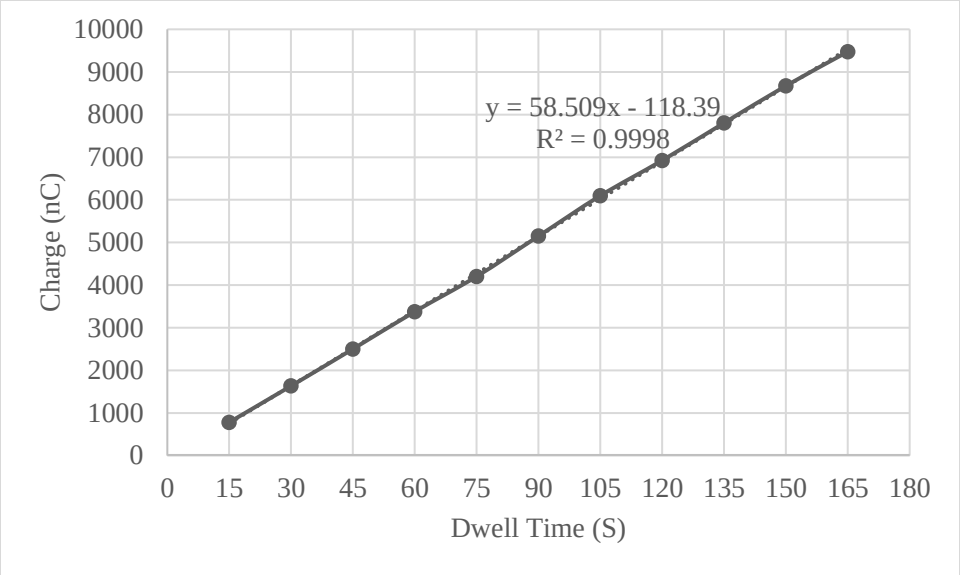


Figure 4.3: Effective transit time determined using the graphical method.

The effective transit time was determined by two methods. Note that the effective transit time is the interdwell transit time. The methods include;

Effective transit time computed using the multiple exposure method as follows with values substituted from Table 4.2;

$t_{eff.tr} = \frac{(E_m - E_s)t}{(mE_s - E_m)}$, ……..…….. 4.2

where; Multiple exposure = 7669.37 nC

Single exposure = 7449.30 nC

Effective transit time = 2.02s

Transit time obtained using linear regression from the general equation;

$q_n = I.t_2 + q_{0.}$ ……..…….…… 4.3

Comparing with equation from graph (see Figure 4.3) and taking effective transit time, $t_{eff.tr}$ as;

$t_{eff.tr} = \frac{q_0}{I}$. ……...……... 4.4

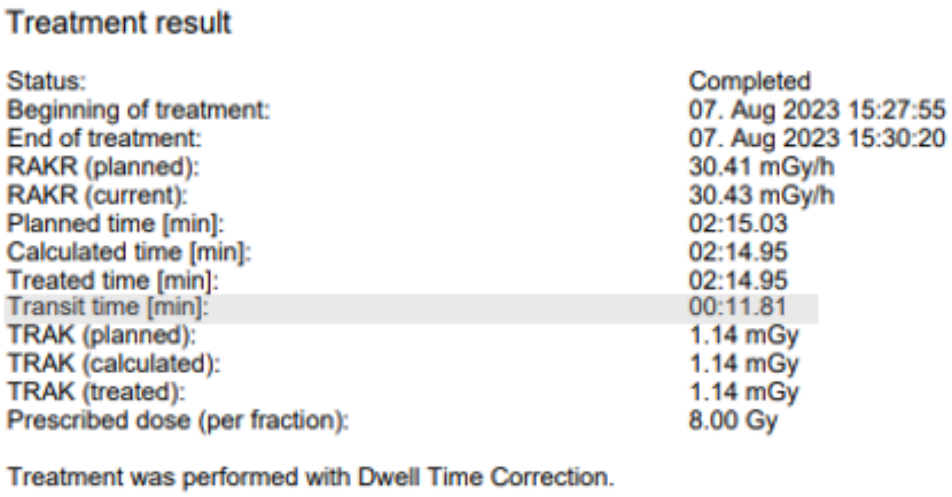
Graph equation$= 58.509x - 118.39.$ ……..……...…4.5

where; $I = 58.51$ is the Air kerma current reading

$q_0 = 118.39$ is the y-intercept in this case the transit dose component.

Effective transit time = 2.02 Seconds

As earlier mentioned in Chapter 3 Section 3.5, for the SagiNova® HDR unit it is possible to obtain the entry and exit transit time since the system provides a report after a plan delivery is complete (see Figure 4.4).



Treatment result

Status:	Completed
Beginning of treatment:	07. Aug 2023 15:27:55
End of treatment:	07. Aug 2023 15:30:20
RAKR (planned):	30.41 mGy/h
RAKR (current):	30.43 mGy/h
Planned time [min]:	02:15.03
Calculated time [min]:	02:14.95
Treated time [min]:	02:14.95
Transit time [min]:	00:11.81
TRAK (planned):	1.14 mGy
TRAK (calculated):	1.14 mGy
TRAK (treated):	1.14 mGy
Prescribed dose (per fraction):	8.00 Gy

Treatment was performed with Dwell Time Correction.

Figure 4.4: Treatment report after a completed plan delivery.

The following Table 4.4 presents entry and exit transit time as reported after the different set up plans were delivered.

Table 4.4: Entry and exit transit time

	Multiple exposure	**Graphical solution**
Reading 1	11.77s	11.94s
Reading 2	11.77s	11.91s
Reading 3	11.81s	12.05s
Average	**11.78s**	**11.97s**

After obtaining the entry and exit transit time, the overall effective transit time was computed to be 13.80s and 13.99s for the multiple exposure method and graphical method respectively (see Table 4.5).

Table 4.5: Overall effective transit time

	Multiple exposure method	**Graphical solution**
Entry and exit	11.78s	11.97s
Effective transit time	2.02 s	2.02 s
Overall Effective transit time	**13.80s**	**13.99s**

4.3 TRANSIT DOSE COMPONENT OF THE IR-192 HDR BRACHYTHERAPY SOURCE

4.3.1 VARIOUS SOURCE STRENGTHS AND DWELLING TIMES.

The activity of a new Ir-192 source, is generally around 10Ci which is about 40.82 mGy.m^2/h in terms of Reference Air Kerma Rate (RAKR) at delivery. With a decay factor of 0.6419, it ranges

to about 3.2Ci which is about 13.06 mGy.m^2/h at replacement for a low activity source. Patients are usually prescribed 6 – 9 Gy with 2 – 4 fractions depending on the clinician's assessment and desired clinical outcome.

If a source of 36.69 mGy.m^2/h delivers 10.34 mGy for 16.55min and a source of 16.22 mGy.m^2/h delivers the same 10.34 mGy for 38.23min whereas a source of 44.21 mGy.m^2/h delivers the same in 14.03min (see Figure 4.5). This dose is expressed as Total Refence Air Kerma (TRAK), the product of Air kerma strength and time which quantifies the amount of energy deposited in air by the source at 1 meter. TRAK is important in treatment planning because it is used as a reference point to calculate the dose that will be delivered to the target tissue. The calculation algorithm models how the radiation interacts with the surrounding tissues.

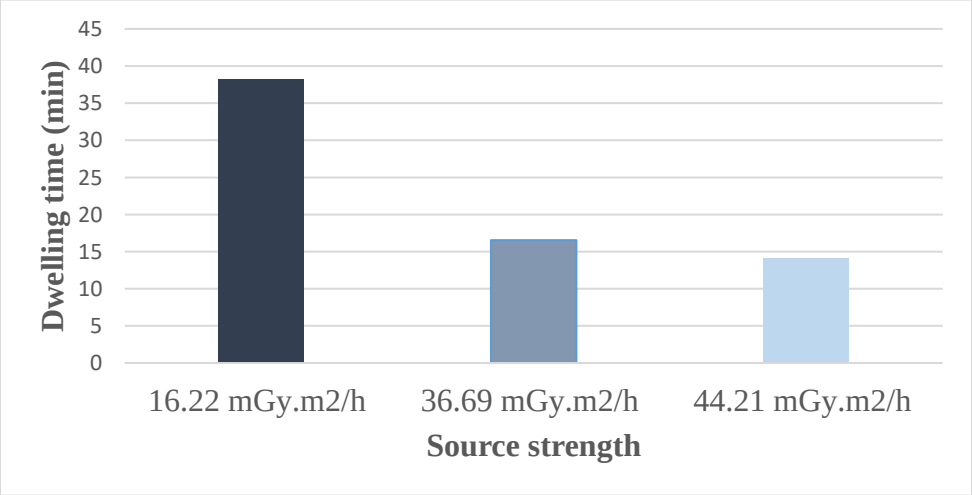


Figure 4.5 Varying source strengths and dwelling times for similar dose.

4.3.2 DIFFERENT SOURCE CONFIGURATIONS

A source of 36.69 mGy.m^2/h delivers 10.34 mGy for a duration of 16.55min using a single dwell position. For the same source to deliver 10.34mGy to the same point of interest using three dwelling positions, the summed treatment time would be 16.69min. The transit time of 13.80s for

the source would deliver an additional 0.07mGy which is 0.68% more to the planned dose. If three independent source transfers were used to deliver the same dose, the summed treatment time would be 16.90min. The source transit time of 35.37s would cause an additional 0.21mGy which adds 2.03% more dose to the planned dose.

Assuming the 36.69 mGy.m^2/h source delivered 8Gy to the same position using three different dwelling positions for the source, with a transit time of 13.80s the source would deliver an increassed 0.07mGy which is $< 1\%$ of planned dose and is negligible. If three independent source transfers were used to deliver the same 8Gy, the source transit time of 35.37s would cause an additional 0.21mGy which is $< 1\%$ of planned dose and is negligible.

The percentage of transit dose contribution would consequently fluctuate based on how long the source is programmed to dwell and the chosen source configuration. As dwell time decreases, the magnitude of the overall effective transit dose increases. This is because the radiation dose delivered at a dwell position, that is the static dose, changes with the programmed dwell time while the transit component remains fairly consistent.

4.4 DISCUSSION

The overall radiation dose received by the patient in each fraction includes both the transit and static doses. The transit dose is mainly due to the radiation emitted by the source as it moves to its first dwell position (entry dose), between activated dwell points (interdwell doses) and during retraction out of the applicator back into the afterloader (exit dose) through the patient's tissues during treatment. The effective transit time (interdwell transit time) for the SagiNova® HDR brachytherapy unit was determined and it was found to be 2.02s. This effective transit time was determined using a multiple exposure method as well as a graphical solution method as presented in Chapter 4 Section 4.2. Furthermore, the overall effective transit time was determined to be about 13.80s and 13.99s using the multiple exposure method and the graphical solution respectively as shown in Table 4.5. Note that the overall effective transit time is the total sum of the entry and exit transit time, and the effective transit time. It is necessary to compute the overall effective transit time to ensure quality treatment to patient by monitoring unnecessary radiation doses that the patient receives during transit of the radiation source.

The well-type ionization chamber is the recommended equipment for the calibration of brachytherapy sources as they provide an easier and reliable method for regular clinical calibrations than others like thimble ionization chambers. As much as they are recommended, the chamber exhibits some uncertainties. Some common uncertainties in the chamber measurements include;

- Chambers used for HDR sources tends to depend on temperature. Introducing an Ir-192 HDR source with exceptionally high activity may lead to an elevation in temperature within the chamber. To mitigate this effect, chambers are designed with an insert that has a material with insulating properties such as Styrofoam. The chamber is also placed in the

bunker for a minimum of 30 minutes prior to measurements to allow for equilibrium with the bunker temperature.

- Pressure decrease from gradual leakage of gas; for sealed chambers, the difference in atmospheric pressure and the high ambient pressure causes leakage which in turn affects chamber sensitivity. In this case a calibration factor is applied to correct for temperature and pressure.
- Scatter effect; this chambers are highly susceptible to the scatter effect of radiation. To minimize scatter radiation reaching the chamber, it is advised to position it at a distance of at least 1 meter from any scattering surface.
- Positioning uncertainty; this happens when the source is inaccurately positioned to the chamber's reference position.
- Recombination losses uncertainties occur when a very high activity source is used. With such sources, the chambers may produce high ionization currents, causing recombination losses requiring correction. Correction for recombination losses is required if an adjustment for how efficient the chamber's collection is was applied during the chamber's calibration process and subsequently incorporated into the chamber's calibration factor.

A multiple exposure method was used, involving different source configurations, to obtain the integrated charge measurements and determine the effective transit time. The average charge obtained using the multiple exposure technique (see Figure 4.2) was about 7669.37nC for the multiple exposure and 7449.30nC for the single exposure. Utilizing Equation 4.2, the transit time was 2.02s. In practical terms, if the reading for one measurement setup differs from another when both measurements are taken for the same duration, it indicates the presence of a transit effect.

This study demonstrates a transit effect, evident in the varying readings observed for different source configurations.

The graphical method was also applied and the effective transit time determined by using linear regression for zero exposure as an intercept on the time axis. Utilizing Equation 4.4, the effective transit time was 2.02s.

The entry and exit transit time was obtained from the system report after the plan delivery was complete as 11.78s and 11.97s for the multiple exposure technique and the graphical method respectively. The overall effective transit time was found to be 13.80s when the multiple exposure technique was utilized and 13.99s when the graphical method was applied as indicated in Table 4.4. Therefore, it is clear that the entry and exit transit time contributed majority to the overall effective transit time. Majority of the dose received during this entry and exit transit time goes to the whole body as the source is not within the applicator inserted next to the tumor. The transit dose would exhibit a decrease following an inverse square pattern as the distance increases.

From Chapter 4 Section 4.3 Subsection 4.3.2, a source of 36.69 mGy.m^2/h delivers 10.34 mGy for a duration of 16.55min using a single dwell position. For the same source to deliver 10.34mGy to the same position using three dwelling positions, the summed treatment time would be 16.69min. The transit time of 13.80s for the source would deliver an additional 0.07mGy which is 0.68% more to the planned dose. If three independent source transfers were used to deliver the same, the summed treatment time would be 16.90min the source transit time of 35.37s would cause an additional 0.21mGy which adds 2.03% more dose to the planned dose. In a clinical context, this discrepancy implies that if a brachytherapy treatment session is interrupted multiple times, or if the treatment is administered using a source with higher activity in numerous small fractions rather than using a source of lower activity but a single longer fraction, then this interruption or

fractionated scheduling could consistently impact the dose delivered particularly if the transit effect adds on a significant percentage.

With the assumption that the 36.69 mGy.m^2/h source delivered 8Gy to the same position using three different dwelling positions for the source, with a source transit time of 13.80s the source would deliver an increased 0.07mGy which is $< 1\%$ of planned dose and is negligible. If three independent source transfers were used to deliver the same 8Gy, the source transit time of 35.37s would cause an additional 0.21mGy which is $< 1\%$ of planned dose and is still negligible. The magnitude of the transit dose becomes more pronounced when source stationary dwelling time decreases, source activity increases, or when there is an increase in applicators and channels used. The transit dose significance is influenced by factors such as source activity, patient prescription, fraction count and source configuration.

Most treatment planning systems typically exclude the transit dose component when calculating patient dose. They assume that the dose considered clinically significant is only delivered when the source remains stationary, and that the dose administered at a specific point is directly proportional with the duration the source dwells at that position.

Administering doses in high doses at an instance increases the biologic effective doses which increase the rate of late tissue effects. Radiobiology indicates that administering treatment in fractions for HDR brachytherapy lowers the rate of late tissue effects. During this fractionated treatments the component of source movement is a factor, the transit dose is directly proportional to the number of fractions. In a situation where the source goes through ‘m’ cycles for entering and exiting to the dwell position, the transit dose would be greater m times that of a singular cycle. Therefore, when there is an interruption in brachytherapy treatment delivery or a fractionated treatment plan is incorporated, it would be necessary to factor in adjustments for source transit.

This research findings closely agree with the reports by, Bastin *et al*. (1992), Wong *et al*. (2001), Ade (2009) and Kanani *et al*. (2018) as reviewed in Chapter 2. As of the time of writing this report, no compensation for entry and exit transit doses has been documented for the SagiNova® HDR unit. From the results of this study it is not advisable to make this assumption because it shows that the transit dose component depends on the activity and configuration of the source, prescribed dose and the quantity of treatment fractions used.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The overall effective transit time for the Bebig SagiNova® HDR unit was determined using two configuration techniques and analyzed using two different methods namely; the multiple exposure method and the graphical solution. The following may be concluded;

i. Effective transit time of 2.02s was obtained with the multiple exposure method, as well as the graphical solution method (see Chapter 4 Section 4.2). The effective transit time was not influenced by the analysis technique.

ii. The overall effective transit time for the SagiNova® HDR unit was determined to be about 13.80s and 13.99s using the multiple exposure method and the graphical solution respectively as depicted in Table 4.5. The entry and exit transit time contributed majority to the overall effective transit time. For instance, 11.78s for the multiple exposure method and 11.97s for the graphical solution as compared to an effective transit time of 2.02s from both methods (see Chapter 4 Section 4.2).

iii. It is not clear the significance of the amount of dose during transit because the transit dose component depends on the activity and configuration of the source, prescribed dose and the quantity of treatment fractions used (see Chapter 4 Section 4.3).

5.2 RECOMMENDATIONS

As discussed, compensation may be required depending on the significance of the transit dose. It is recommended that this can be done during treatment prescription or during planning on the treatment planning system. During plan optimization, this can be done by perhaps reducing dwelling times which in turn reduces the static dose, accommodating the transit doses.

In future research, it would be valuable to broaden the scope of this study to determine precisely how much dose is received by the organs proximal to the path followed by the source during transit. It may involve refining the experimental protocols or employing more advanced data collection techniques.

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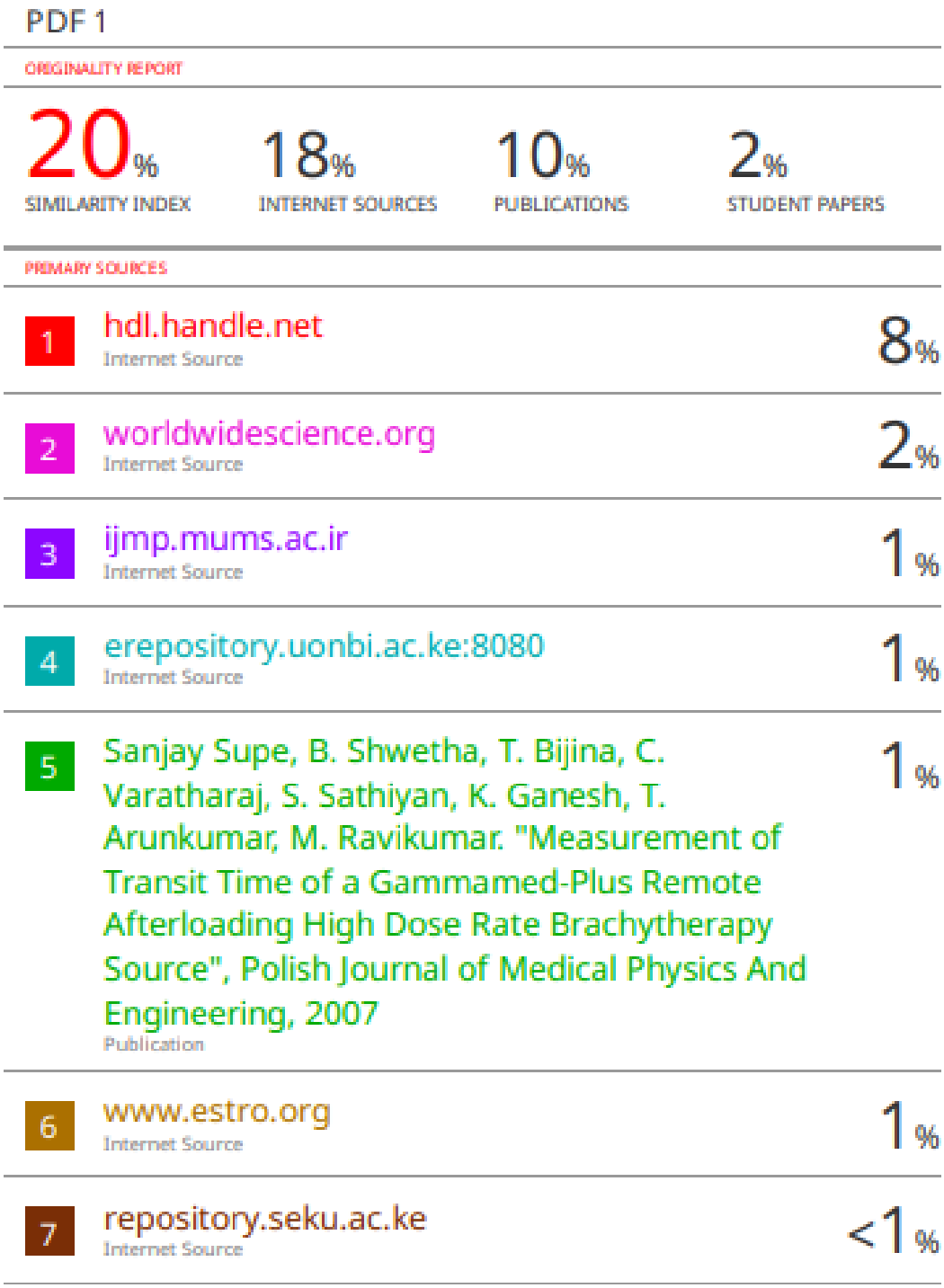
APPENDIX: Plagiarism report



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