DOSIMETRY COMPARISON OF AAPM TG-43 AND MONTE CARLO CALCULATIONS IN 192IR HDR BRACHYTHERAPY FOR PATIENTS WITH TONGUE CANCER USING EGS_BRACHY SOURCE CODE

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by

FATIN HANIS BINTI MOHD ROSLI

Dissertation submitted in partial fulfillment
of the requirements for the degree
of Bachelor of Health Science (Honours) (Medical Radiation)

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CERTIFICATE

This is certify that the dissertation entitled ‘Dosimetriy Comparison Of AAPM TG-43 And Monte Carlo Calculations In 192Ir HDR Brachytherapy For Patients With Tongue Cancer Using Egs_brachy Source Code’ is a bona-fide record of research work done by Fatin Hanis Binti Mohd Rosli (156371) during the period of October 2024 to July 2025 under my supervision. I have read this dissertation and that in my opinion it conforms to acceptable standards of scholary presentation and is fully adequate, in scope and quality, as a dissertation to be submitted in partial fulfilment for the degree of Bachelor of Health Science (Hons) (Medical Radiation). Research work and collection of data belong to the University Science Malaysia.

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at University Science Malaysia or other institutions, I acknowledge that the research work and collection of data belong to University Science Malaysia. I grant University Science Malaysia the right to use the dissertation for educational or further research purposes.

(FATIN HANIS BINTI MOHD ROSLI)

Date:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
AJCC	American Joint Committee on Cancer
CLRP	Canadian Light Source Radiation Physics
CT	Computed Tomography
CTV	Clinical Target Volume
Co-60	Cobalt-60
DICOM	Digital Imaging and Communications in Medicine
DNA	Deoxyribonucleic acid
DVH	Dose Volume Histogram
EBRT	External Beam Radiotherapy
EGSnrc	Electron Gamma Shower National Research Council
Egs_brachy	Electron Gamma Shower Brachytherapy
eb_gui	egs_brachy graphical user interface
GATE	Geant4 Application for Tomographic Emission
GEC ESTRO/ACROP	Guideline committees under the European Society for Radiotherapy and Oncology
GTV	Gross Tumor Volume
HDR	High Dose Rate
HI	Homogeneity Index
HPV	Human Papillomavirus
HU	Hounsfield Units
IGRT	Image-Guided Radiation Therapy

IMRT	Intensity-Modulated Radiation Therapy
Ir-192	Iridium-192
LDR	Low Dose Rate
MAR	Material Attenuation Replacement
MBDCAa	Modal-Based Dose Calculation Algorithm
MC	Monte Carlo
MDR	Medium Dose Rate
MRI	Magnetic Resonance Imaging
OAR	Organ At Risk
PTV	Planning Target Volume
RT	Radiation Therapy
STR	Simple Threshold Replacement
TAS	Tissue Assignment Schemes
TG-43	Task Group No. 43
TNM	Tumor-Node-Metastasis
TPS	Treatment Planning System
VPM	Virtual Patient Modal

LIST OF SYMBOLS

$\bar{g}$	average
Gy	Gray
h	Hour
cm	Centimeter
keV	Kilo electron Volt
MeV	Mega electron Volt
GeV	Giga electron Volt
K	kerma
K_{col}	Collision kerma
$\frac{\bar{\mu}\bar{tr}}{\bar{\rho}}$	Energy fluence averaged mass-energy transfer coefficient
$\frac{\mu en}{\rho}$	Energy fluence averaged mass-energy absorption coefficient
Ei	Energy photon traversing voxel
V_j	Voxel volume
t_i	Track-length of a photon through voxel
cGy	Centi Gray
mm	Milli meter
HU	Hounsfield Units
$[SK]_{maxx}$	Starting (t = 0) source air-kerma strength
S_K^{hist}	Air-kerma strength per history
Δt_{max}	Maximum individual dwell time

ABSTRAK

Brakiterapi kadar dos tinggi (HDR) yang menggunakan Iridium-192 ialah teknik yang diiktiraf untuk rawatan kanser lidah, memberikan manfaat untuk memberikan dos yang sangat konformal sambil melindungi struktur kritikal yang bersebelahan. *The American Association of Physicists in Medicine Task Group 43 (AAPM TG-43) formalisme* berfungsi sebagai standard klinikal yang lazim untuk pengiraan dos; walau bagaimanapun, ia beroperasi di bawah andaian persekitaran air yang seragam, dengan itu mengabaikan perbezaan anatomi khusus pesakit. Kajian ini mengkaji variasi pendekatan antara AAPM TG-43 dan simulasi Monte Carlo (MC) menggunakan aplikasi egs_brachy, yang memudahkan pengiraan dos khusus pesakit yang lebih tepat dengan menggabungkan heterogeniti.

Dataset CT daripada tiga pesakit dengan kanser lidah yang menjalani brakiterapi HDR telah diteliti. Pelan rawatan berdasarkan AAPM TG-43 telah dibuat menggunakan Sistem Perancangan Rawatan (TPS) Oncentra Braki . Selepas itu, rancangan ini telah dipindahkan ke dalam rangka kerja simulasi MC egs_brachy melalui antara muka eb_gui, membolehkan pemodelan berasaskan voxel anatomi pesakit dan simulasi pengagihan dos dengan skema penugasan tisu terperinci. Histogram Isipadu Dos (DVH) dan metrik statistik seperti D_{90}, D_{100} untuk Isipadu Sasaran Perancangan (PTV), dan $D_{0.1cc}$, $D_{1.0cc}$ dan $D_{2.0cc}$ untuk organ berisiko (OAR) dinilai merentas kedua-dua metodologi. Keputusan menunjukkan perbezaan ketara dalam parameter dosimetri antara simulasi AAPM TG-43 dan MC. Pendekatan AAPM TG-43 biasanya melebihkan dos kepada GTV sambil meremehkan dos kepada OAR tertentu, menonjolkan batasannya dalam menangani kerumitan anatomi khusus

pesakit. Penemuan ini menekankan janji simulasi MC menggunakan egs_brachy sebagai alternatif yang lebih tepat dan boleh dipercayai untuk pengiraan dos dalam brakiterapi HDR, terutamanya di kawasan anatomi yang rumit seperti rongga mulut.

ABSTRACT

High-dose-rate (HDR) brachytherapy employing Iridium-192 is a recognized technique for the treatment of tongue cancer, providing the benefit of delivering highly conformal doses while protecting adjacent critical structures. The American Association of Physicists in Medicine Task Group 43 (AAPM TG 43) formalism serves as the prevailing clinical standard for dose calculations; however, it operates under the assumption of a uniform water environment, thereby overlooking patient-specific anatomical differences. This study examines the variances between the AAPM TG 43 formalism and Monte Carlo (MC) simulations utilizing the egs_brachy application, which facilitates more precise patient-specific dose calculations by incorporating heterogeneities.

CT datasets from three patients with tongue cancer who underwent HDR brachytherapy were examined. Treatment plans based on AAPM TG-43 were created using the Oncentra Brachy Treatment Planning System (TPS). Subsequently, these plans were transferred into the egs_brachy MC simulation framework through the eb_gui interface, enabling voxel-based modeling of patient anatomy and the simulation of dose distributions with detailed tissue assignment schemes. Dose Volume Histograms (DVHs) and statistical metrics such as D_{90}, D_{100} for the Planning Target Volume (PTV), and $D_{0.1cc}$, $D_{1.0cc}$, and $D_{2.0cc}$ for organs at risk (OARs) were evaluated across both methodologies. The results indicated significant differences in the dosimetric parameters between the AAPM TG-43 and MC simulations. The AAPM TG-43 approach typically overestimated doses to the GTV while underestimating doses to specific OARs, highlighting its limitations in addressing patient-specific anatomical complexities. These findings emphasize the potential of MC simulations

using egs_brachy as a more precise and reliable alternative for dose calculation in HDR brachytherapy, especially in anatomically intricate regions such as the oral cavity.

CHAPTER 1 - INTRODUCTION

1.1 Background of study:

Tongue cancer refers to cancer that arises from the large flat cells on the lining of the tongue which is a type of head and neck cancer. It can be categorized into two main types of oral tongue cancer that arises in the anterior two thirds of the tongue and oropharyngeal cancer, which arises at the base of the tongue. Consequently, visible symptoms generally include sores, pain, swallowing impairment and speech alterations. Management includes surgery, radiation therapy and chemotherapy although this depends on the stage and site of cancer [1] .

HDR brachytherapy is a type of internal radiation therapy that is applicable in the localized cancers for instance, tongue cancer. In this technique a radioactive source like Iridium-192 is either implanted within the isocenter or placed close to the tumor. HDR brachytherapy offers an opportunity to irradiate the tumor with high doses of radiation while sparing the neighboring healthy tissue. Ir-192 sources are favored for application in HDR brachytherapy treatment because of high specific activity and half-life that allows high doses accuracy and sufficient tumor eradication. HDR brachytherapy of tongue cancer usually practices interstitial approach in which catheters are placed in tongue tissues to direct the radioactive source to the target tumor site. This method enables a precise control of the radiation dose distribution so that tumor receives its optimum dose while sparing relevant structures in the region like the salivary glands and the mandible [2].

The treatment is often delivered in several sessions. Each session takes from several minutes only which is more comfortable for the patient compared to external beam radiation therapy (EBRT) [3]. Thus, HDR brachytherapy has some advantages such as rapid dose fall off, the dose drops off steeply outside the target volume. This characteristic is well manifested in the oral cavity since location of the implant often requires maintenance of functionality of surrounding tissues. Furthermore, HDR brachytherapy can be integrated with EBRT to boost the chance of local control and therefore the general treatment result [4].

The treatment process associated with HDR brachytherapy is multifaceted and key elements include treatment planning, catheter implantations and the actual therapy session. X-ray, CT or MRI scans to prepare specific maps on how to place catheters or how to give the source and treatment. The aid of computer simulations and optimization algorithms assist in delivering the uniform dose to the affected tumor and at the same time minimizing the dose delivered to the surrounding normal tissues [2]. During the treatment planning, it is also clearly diagnosed where exactly the tumor is and its size. These details are then applied when formulating a schedule that defines the number of catheters needed and where they are to be located, positions that the source has to adopt, as well as the time spent emitting radiation in each position. The aim is to deliver the greatest possible tumor dose per measured fraction while limiting irradiation of healthy tissues.

The AAPM TG-43 report is a landmark document in the brachytherapy profession, especially for HDR treatment of cancers including tongue cancer. First released in 1995, and revised as the TG-43U1, this represents a common procedure for calculation of dose fields around photon irradiating brachytherapy sources. The TG-43 formalism brings the geometry of the radiation dose distribution into the more accessible polar coordinate form for more

accurate determination of dose rates in different sphere radius relative to the source. In accordance with the findings of the report, air-kerma strength is among the most significant factors, which characterizes the radiation of the source and the effect on the tissues of the body. It also brought important modifications defining, for example, the exclusion of the apparent activity in favor of the direct specification of the source strength, and the substitution of the anisotropy constant by the distance-dependent one-dimensional anisotropy function for the enhancement of the accuracy of doses calculations [5].

In HDR brachytherapy of tongue cancer where accuracy is paramount especially by proximity to vital structures, TG-43 gives valuable dose factors such as dose rate factors and radial dose tables. These parameters bear significance in the case of TPS and make it possible for radiation oncologists to perform the rigid therapy while causing harm or even destructive impacts to the health-compromised tissues near the tumorous regions. TG-43 has been proven by several studies, the studies that use Monte Carlo simulation support the usability of TG-43 in clinical setups. Thus, following TG-43 is essential to achieve the outcomes proposed in the methodology, in practical healthcare contexts [6].

Monte Carlo simulation is one of the powerful computational tools for computing dose distributions available in the field of radiation therapy and it is more commonly used for planning the treatment in tongue cancer patients. This technique is based on probability simulations and uses statistical sampling to simulate complicated relations between radiation and material to accurately estimate dose distributions and therapeutic effects. If referring to tongue cancer, Monte Carlo simulations can be used for analyzing one or the other aspect of HDR brachytherapy as it is one of the most widely used treatments for the mentioned type of malignancy [7]. The other advantage of Monte Carlo simulations in HDR brachytherapy

is the real time prediction of the three-dimensional iso-center dose distribution around implanted radioactive sources in or near the tumor. These factors include factors such as tissue inhomogeneity, source shape and orientation, and the individual differences of patient anatomy which can be addressed by Monte Carlo methods due to its ability to model emitted radiation interactions with tissues. The level of detail is important for the treatment of tumors positioned in complicated areas of the human body such as the tongue where it would be difficult to treat the tumor without affecting the neighboring healthy tissues [8].

Egs_brachy developed from the EGSnrc code system is a fast, efficient and versatile Monte Carlo system specifically for brachytherapy therapy photon and electron sources. This software offers a complete package of tools designed to improve dose calculation that is critical in cancer treatment. The system has numerous features and capabilities dose scoring is one of it; where its results in dose calculations through tracklength estimator or interaction scoring to produce accurate dose distributions around brachytherapy sources. Furthermore, it is impossible when using egs_brachy to distinguish between primary and scatter dose and this is important for the determination of the relative contribution of the various interactions of the radiation with the tumor and the surrounding tissues [9]. The application also features the ability to recycle particles during several source simulations which helps the analyst to build models within shorter time as compared to when one had to simulate a single source at a time. In addition, it contains additional features like enhanced Bremsstrahlung production cross-section and uniform Bremsstrahlung split, which are useful for performing simulations of electronic brachytherapy where secondary radiation contribution is relatively high. It has a library of geometries of brachytherapy sources which facilitates the good modeling of many clinical situations. It can therefore be a valuable tool for investigators and practitioners who

confront the fine points of the spatial dosimetry in brachytherapy when making modifications towards the treatment regimen. It features an interface that ranges from easy to use for enthusiasts and laymen yet possesses high performance capabilities for experts and professionals in Monte Carlo methods of radiation therapy [9].

1.2 Problem statement

The AAPM TG-43 formalism has been the reference for dosimetric computations of Ir-192 HDR brachytherapy. However, a limitation of the TG-43 formalism is that dosimetric heterogeneities related to individual anatomical changes are also approximated [10]. These are particularly undesirable in large anatomic structures such as the tongue where accurate dose delivery is desirable for optimal tumor control and reduction of side effects.

However, Monte Carlo (MC) simulations, such as the egs_brachy source code, are much more specific in that they are based on patient-specific shapes and tissue types. Despite the fact that these simulations could provide potential benefits, their application in clinical practice for HDR brachytherapy is currently rather restricted due to the lack of comprehensive comparative evaluations.

It is therefore important to conduct this study to systematically compare the dosimetric results of TG-43 and Monte Carlo simulations to establish how each affects clinical dosimetry and to highlight the limitations of the TG-43 formalism as well as the efficiencies of Monte Carlo simulations in improving dose accuracy and efficiency of treatment planning.

1.3 Research Question

1. How can a Monte Carlo model be effectively established for brachytherapy treatment specifically targeting tongue cancer?
2. What are the validation criteria for the EGS_Brachy source code when comparing to the Monte Carlo with TG-43 formalism?
3. How to calculate the differences of AAPM TG-43 and Monte Carlo calculation in the tongue cancer patients?

1.4 Objective

1.4.1 General Objective

To compare the AAPM TG-43 in the treatment of tongue cancer patients with Monte Carlo calculation using EGS brachy source code.

1.4.2 Specific Objective

1. To establish the Monte Carlo model for tongue brachytherapy treatment.
2. To validate the egs_brachy source code by comparing results with established of TG-43 formalism.
3. To calculate the differences of AAPM TG-43 and Monte Carlo calculation in tongue cancer patients.

1.5 Significant of study

This study holds considerable significance in the field of brachytherapy dosimetry, its potential to refine and enhance the accuracy of radiation dose calculations for brachytherapy treatments. Monte Carlo simulations provide a highly detailed and statistically

accurate method for modeling radiation transport and interaction, making them invaluable for optimizing treatment plans. By comparing the simulation results with the widely accepted TG-43 formalism, this research seeks to address discrepancies and improve the precision of radiation delivery, ultimately leading to better treatment effectiveness and patient safety.

Furthermore, validating the EGS_Brachy source code is essential for ensuring the reliability of computational tools used in treatment planning. Establishing confidence in these models will support their integration into clinical practice, providing oncologists with more precise calculations for individualized patient treatments. This research may also contribute to the broader medical physics community by offering insights into brachytherapy optimization for other cancers beyond tongue cancer.

CHAPTER 2 - LITERATURE REVIEW

2.1 Tongue Cancer

It is the most common form of mouth/oral cancer, squamous cell carcinoma being the predominant type, and remains a significant worldwide public health burden, despite improvements in prevention and management. According to the Global Cancer Observatory, oral tongue cancer is still one of the major causes of head and neck cancer, and its incidence is increasing in some regions, particularly among those who are under 45 years of age [11]. This rise is attributed to shifting epidemiology patterns, which include shifts in etiological agents.

The risk factors associated with squamous cell carcinoma of the tongue continue to encompass traditional elements such as tobacco use, whether through smoking or smokeless forms, alongside alcohol consumption. These two factors work synergistically to elevate the risk of cancer by damaging the epithelium and facilitating mutagenesis [12]. However, there is a growing recognition of HPV (human papillomavirus) as a new potential risk factor. HPV positivity was present in roughly 15-20% of patients diagnosed with oral tongue cancers, particularly among younger, non-smoking individuals. This finding aligns with the trends observed in oropharyngeal cancers and suggests that HPV testing could be beneficial in the diagnostic evaluation of tongue cancers [13].

The clinical manifestations are typically characterized by ulcerations or exophytic masses that present as persistent lesions on the lateral or ventral surfaces of the tongue. Most patients report accompanying symptoms such as discomfort, bleeding, dysphagia, or changes

in speech [14]. The gold standard for diagnosis includes physical examination and biopsy, with staging adhering to the 8th edition of the AJCC's TNM classification system [15]. Early-stage tumors (T1–T2, N0) generally have a favorable prognosis, with a 5-year survival rate of 70–80%. Conversely, tumors that are larger or node-positive exhibit significantly poorer outcomes, underscoring the critical nature of early diagnosis [15].

Concerning treatment, the established standard of care for early-stage disease involves surgical resection with sufficient margins [16]. In instances exhibiting high-risk characteristics such as perineural invasion and lymphovascular invasion, adjuvant radiotherapy is typically recommended and may be instrumental in addressing the considerable consequences that surgical interventions have on speech and swallowing capabilities particularly in cases of tongue cancers leading to the formulation of organ preservation strategies [17]. Among these strategies, high-dose-rate (HDR) brachytherapy has demonstrated significant potential, as it can deliver highly conformal radiation doses directly to the tumor while minimizing exposure to critical surrounding areas.

In situations involving early-stage or superficial lesions, HDR brachytherapy alone may achieve effective local control, whereas in more advanced scenarios, it acts as an enhancement following external beam radiotherapy (EBRT).Recent clinical studies have reported outstanding outcomes from HDR brachytherapy, with local control rates exceeding 85%–90%; functional outcomes include the preservation of speech and swallowing abilities [19]. Moreover, various studies have indicated that when HDR brachytherapy is conducted under image guidance (CT or MRI), with meticulous attention to treatment planning regarding source positioning and dwell time, it can yield results comparable to surgical intervention, albeit with reduced morbidity.

Various prognostic factors linked to the survival of individuals with tongue cancer encompass stage, nodal status, and HPV status. The patients with HPV-positive tongue cancers had a 25% lower risk of mortality compared to those with HPV-negative tongue cancers, irrespective of the treatment approach employed [20] Click or tap here to enter text.. Additionally, other patient-related characteristics, particularly comorbidities in older populations, significantly influence the tolerability of treatments and ultimately inform treatment decisions [22].

Despite the improvements in mortality rates attributed to advancements in therapeutic interventions, maintaining a high quality of life remains a primary concern. Patients who have undergone surgical procedures frequently face enduring challenges with speech and swallowing, necessitating rehabilitation assistance [22]. Conversely, HDR brachytherapy is recognized for its expedited recovery periods and enhanced preservation of organ function; however, it may also lead to adverse effects such as mucositis, fibrosis, and alterations in taste [21]. To address these complications, contemporary protocols are integrating dose optimization and advanced planning methodologies, including Monte Carlo–guided plans, aimed at minimizing high-dose exposure to non-target tissues.

2.2 Radiation Therapy

Radiation refers to the transmission of energy through either space or matter, manifesting as waves or subatomic particles [31]. Since the late 19th century, radiation has significantly contributed to cancer treatment, following Röentgen's discovery of X-rays in 1895 and the Curie couple's discovery of radium in 1898 [40]. Radiation can be categorized into non-ionizing and ionizing types, depending on its capacity to ionize atoms within the medium it traverses. Non-ionizing radiation, which includes radio waves and visible light,

does not possess enough energy to displace electrons from atoms. Conversely, ionizing radiation, such as X-rays and gamma rays, carries sufficient energy to ionize atoms, rendering it extremely valuable in medical practices like diagnostic imaging and cancer therapy. Nonetheless, ionizing radiation poses a risk of cellular damage; thus, its application in medicine necessitates stringent control and monitoring to safeguard patient health.

Radiation toxicity is an essential consideration when utilizing radiation for cancer therapy. Upon contact, radiation ionizes the atoms or molecules within the affected tissue by either absorbing or emitting electrons. These ions may subsequently interact with nearby tissues, potentially causing damage to the DNA of the cells. Given these properties, radiation is employed to destroy the DNA of cancer cells, although it can also harm the DNA of surrounding organs. The latter cells typically demonstrate a higher likelihood of recovery, while cancer cells have a reduced ability to repair [38].

Dose refers to the amount of energy deposited from ionizing radiation in matter per unit mass. The SI unit for this measurement is Gray (Gy), equivalent to 1 joule per kilogram. The dose is distributed in the target tissue and adjacent normal tissue structures throughout the radiation treatment process [31]. The distribution of dose is quite complex, depending on the anatomical structure involved. Consequently, assessing this intricate dose distribution necessitates the use of various tools and metrics. The Dose-Volume Histogram (DVH) is a common metric used for this purpose. DVH aggregates all dose information for a given structure and summarizes it in a single graph. In its cumulative form, the DVH illustrates the percentage volume of a structure that receives a dose greater than or equal to a specified amount as a function of that dose [31]. For instance, Figure 2.1 emphasizes that two critical metrics for evaluating DVHs are volume (V_x) and dose (D_x). The x-axis denotes the D_x dose

received by the structure, while the y-axis indicates the percentage of the structure's V_x volume that received at least the corresponding D_x , dose on the x-axis. For example, D_{90} of the Clinical Target Volume (CTV) signifies the dose that 90% of the CTV volume has received. Furthermore, the D metrics can also be applied to absolute volumes of a structure. This is frequently utilized when evaluating the dose received by Organs at Risk (OARs) during radiotherapy. For instance, D_{2cc} represents the maximum dose absorbed by 2 cm^3 of the OAR.

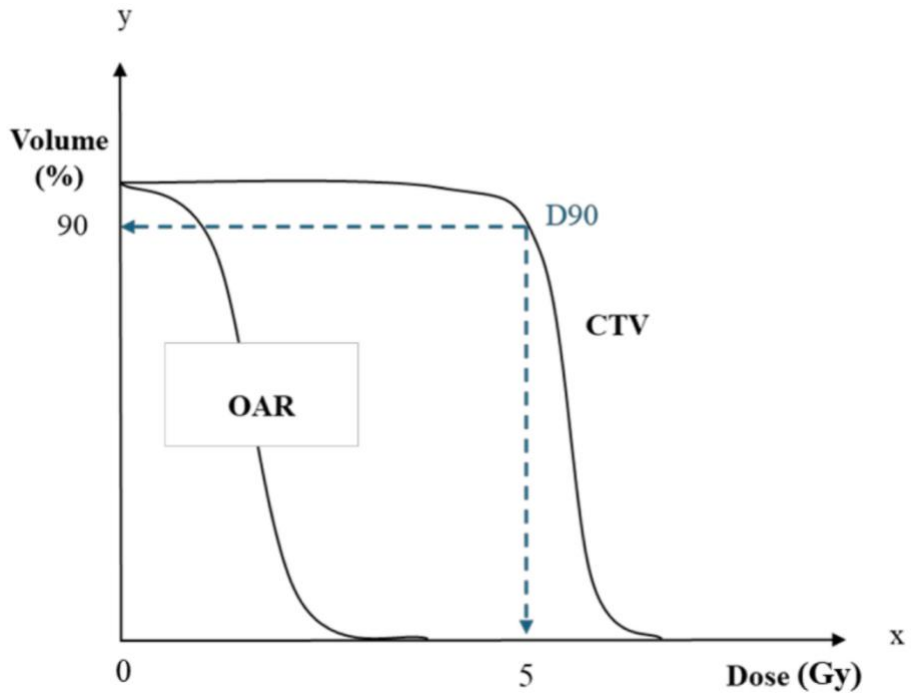

Figure 2-1: An example illustrating how to determine the metric from the DVH of the structures [48].

This treatment can be utilized as a mono-therapy or in combination with chemotherapy and or surgical procedures [31]. Chemotherapy involves the administration of pharmacological agents aimed at destroying or sensitizing tumor cells to radiation, while surgery entails the physical excision of tumors from the patient. Following surgical intervention, microscopic tumor cells may persist, which are subsequently targeted by radiation therapy to reduce the likelihood of recurrence. Radiation therapy (RT) can be

administered in two primary forms: External Beam Radiation Therapy (EBRT), where the radiation is applied from an external source, and internal radiation therapy, such as brachytherapy. EBRT represents the most prevalent type of radiation treatment, encompassing various techniques including 3-D conformal radiation, Intensity-Modulated Radiation Therapy (IMRT), and image-guided radiation therapy (IGRT) [39]. Internal radiation therapy, on the other hand, refers to a method where radioactive materials deliver radiation to a specific area from within the body. The subsequent section will focus on brachytherapy as the treatment modality of interest.

2.3 Brachytherapy

Currently, a variety of radiation therapies are employed in the treatment of cancers. These therapies encompass electromagnetic radiation, such as gamma rays and X-rays, as well as particle radiation, including electron, proton, carbon ion, and neutron beam therapies. Based on the positioning of these radiation sources, radiation therapy is categorized into external beam radiation therapy (EBRT) and brachytherapy. In the case of brachytherapy, the radiation sources are either temporarily or permanently inserted within or in proximity to the tumor. The majority of radiation sources utilized in brachytherapy consist of isotopes that emit low-energy gamma radiation. This method offers the benefit of administering a high-dose treatment directly to the tumor while simultaneously safeguarding the surrounding organs at risk (OAR). To accurately deliver the radiation dose to the tumor, brachytherapy applicators are necessary to position the radiation isotopes within the body. A range of applicator types, including interstitial needles, have been designed and utilized for tumor treatment; their configurations are informed by the tumor's type, location, and shape, as well as the treatment methodologies employed, such as high-dose-rate (HDR) and low-dose-rate

(LDR) brachytherapy. These applicators are commonly applied in the treatment of prostate, breast, gynecological, and skin cancers. Recently, there have been numerous efforts to incorporate intensity modulation techniques into the field of brachytherapy, leading to the development of innovative needles and applicators [23].

2.3.1 Types

Brachytherapy can be classified with respect to the treatment time (temporary or permanent) but also with respect to the dose rate of the source. HDR is when the source delivers more than 12 Gy/h and LDR is when it delivers 0.4–2 Gy/h [24]. The most commonly used isotope for HDR is the photon-emitting Iridium-192 (192Ir) with a half-life of 73.83 days. Other isotopes used for HDR sources are Cs-137 and Co-60 [24].

2.3.2 Source models

Brachytherapy sources are manufactured into different models by a variety of companies. These source models will have different materials used in their construction as well as different sizes and dimensions available through the manufacturer. Some common 192Ir source models are MBDCA-WG, VariSourceVS2000, Flexisource, microSelectron-v2r,… Schematics of the structure of the two seeds used in this thesis, the MBDCA-WG and microSelectron-v2r are given in Figure 2.2 and Figure 2.3 respectively.

Figure 2-2*:* The MBDCA-WG consists of a 3.50 mm long 192Ir core with a diameter of 0.6 mm enclosed in a stainless steel capsule (AISI 316L with a density of 8.02 g/cm3). The mean photon energy is 360,63 keV [25]

Figure 2-3: The mHDR-v2r consists of a 3.50 mm long cylindrical 192Ir core with a diameter of 0.60 mm enclosed in a 0.90 mm diameter AISI 316L stainless steel capsule (density 8.06g/cm3) with a small layer of air around the core. The mean photon energy is 360,53 keV [26]

2.3.3 HDR Brachytherapy

High Dose Rate (HDR) brachytherapy continues to be a significant method in the battle against cancer, offering remarkable dose accuracy while reducing harm to adjacent healthy tissues. This is accomplished by positioning a high-activity isotope most commonly Iridium-192 (^{192}Ir), directly at or in close proximity to the tumor location [25]. In contrast to Low Dose Rate (LDR) and Medium Dose Rate (MDR) techniques, HDR delivers radiation in rapid bursts (exceeding 12 Gy/h), facilitating outpatient treatment alternatives and decreasing overall treatment durations. This not only improves patient comfort but also optimizes the workflow within treatment facilities [23].

2.3.4 TG-43 dose calculation

In current clinical standards, dose distribution around the seed was calculated following the recommendations of the TG-43 protocol of AAPM [5].

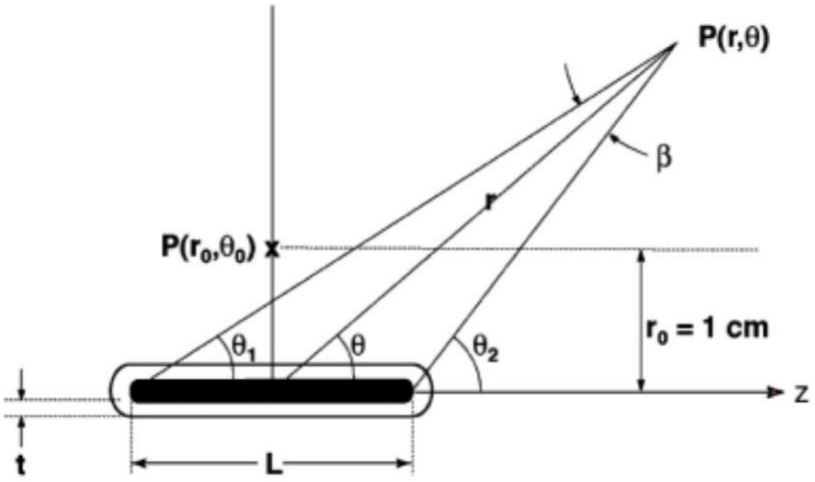

Figure 2-4: The coordinate system used for brachytherapy dosimetry calculations [5]

This formalism is described in terms of a polar coordinate system in Figure 2.4. The reference point (r0, θ0) is chosen on the transverse axis at 1 cm from the center of the source. In this system, the dose rate at any point around the source can be expressed as:

$$\dot{D}(r,\theta) = S_k \times \Lambda \times \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} \times g_L(r) \times F(r,\theta) \qquad (2.1)$$

where: Sk is the air kerma strength of the source (μGy m^2 h^{-1} or cGy cm^2 h^{-1}, also called U), Λ = dose rate constant $= \dot{D}(r_0,\theta_0)/Sk$ $(cGy\,h^{-1}\,U^{-1})$, $G(r,\theta)$ = geometry function $= \beta/(L \times r \times sin(\theta))$ for line source, $g(r)$ = radial dose function $= \dot{D}(r,\theta_0)G(r_0,\theta_0)/(\dot{D}(r_0,\theta_0)G(r,\theta_0)$ and $F(r,\theta)$ = 2D anisotropy function $= \dot{D}(r,\theta_0)G(r,\theta_0)/(\dot{D}(r,\theta_0)G(r,\theta_0)$. More detail on each parameter can be found in TG-43

[5]. When calculating the dose using the TG-43 formula, this formula does not consider tissue heterogeneity. This form only calculates the dose in water, so inheterogeneity adjustments are virtually unnecessary. This is because the distance from the reference point to the source has a much greater influence on the dose than any other factor. TG-43 calculates dose to water which is assumed to be the same as dose to medium in clinical settings. In addition, the formalism assumes an infinite water medium surrounding the sources. These assumptions were considered appropriate for clinical settings since most soft tissues are water-equivalent materials and radiation emitted by brachytherapy sources has a relatively short range. However, this is also one of the limitations of this formalism.

The first limitation is that the patient's body cannot be accurately modeled for each treatment site. The volume within the patient is also considered water under the TG-43 assumption leading to tissue variations not being considered. This will have a greater effect on tissues with densities other than water (e.g., bone) or close-space locations (e.g., lungs) [28], [29]. To clarify the importance of the environment considered in dose calculations, we consider the relationship between collision kerma and absorbed dose [47].

$$D = \beta \times K^{col} = \beta \times \left(\overline{\frac{\mu_{en}}{\rho}}\right) \times \Psi$$

where β is the quotient of the absorbed dose at a given point and the collision part of kerma at the same point, $\overline{\frac{\mu_{en}}{\rho}}$ is the mass-energy absorption coefficient of the medium, and Ψ is the photon energy fluence. From this relationship, it can be seen that in dose calculation there is a direct dependence on the mass-energy absorption coefficient, which can varysignificantly from one environment to another, depending on the mass element composition [27].

A second limitation is that this method also ignores the consideration of high density materials surrounding the source which can lead to inaccuracies with the overall dose distribution. Figure 2.2 and Figure 2.3 shows us a radioactive isotope surrounded by steel. The presence of metallic materials with high Z numbers like this will have an impact on photon interactions and thus dose deposition in nearby particles.

Therefore, to solve the above problems, the MBDCA was used. This algorithm will be found in the next section.

2.4 Model-Based Dose Calculation Algorithm

Given the constraints of TG43, the implementation of model-based dose calculation algorithms (MBDCAs) will be crucial for the progression of brachytherapy treatment planning. MBDCAs, including the collapsed-cone superposition/convolution algorithm, grid-based Boltzmann equation solver, and the MC method, possess the capability to represent the dose distribution with greater precision than TG43 [30].

2.4.1 Monte Carlo Code

The MC method is a commonly employed technique that has numerous applications [31]. MC simulations can require significant time investment; therefore, to optimize time efficiency in treatment planning for brachytherapy, pre-simulated data regarding the characteristics of particles as they exit the source surface may be utilized [30].

2.4.2 EGSnrc Software

EGSnrc (Electron Gamma Shower National Research Council) is a software toolkit used to perform MC simulations of ionizing radiation transport through matter. It models the

propagation of photons, electrons, and positrons with kinetic energies between 1 keV and 10 GeV, in homogeneous materials [32]. egs_nrc has an application called "g" which calculates a variable $\bar{g}$ = average fraction of kinetic energy lost to radiative events for primary photon interactions. Or this application can calculate the radiative yield, Y, for slowing down charged particle beams. In addition to these g also calculates the kerma, K, collision kerma, K_{col}, energy fluence averaged mass-energy transfer coefficient, $\frac{\bar{\mu}\bar{\mathrm{tr}}}{\rho}$, and the energy fluence averaged mass-energy absorption coefficient, $\frac{\mu en}{\rho}$ [31] .

2.4.3 egs++ class library

egs++ serves as an extension of EGSnrc. It encompasses geometry and source packages that enable users to construct more intricate geometries, such as a rectilinear phantom derived from a CT data set referred to as an egsphant [31]. This library facilitates the calculation of dose or collision kerma points within linear voxels or within spherical or cylindrical shells, should such geometries be required, in addition to generating various geometries of the source radiation.

2.4.4 egs_brachy application

egs_brachy is a contemporary application of EGSnrc that utilizes egs++ for the modeling of geometries and particle sources, specifically tailored for brachytherapy applications. Moreover, egs_brachy has contributed to various improvements in the general-purpose egs++ library, introducing new geometry and shape classes.

egs_brachy is capable of performing dose calculations, generating phase-space data, and calculating particle spectra. Additionally, it integrates features aimed at enhancing

simulation efficiency, such as effective radiation transport and geometry modeling, the calculation of collision kerma through the track-length estimator, phase-space sources, particle recycling, and variance reduction techniques for electronic brachytherapy [30]. A significant feature of egs_brachy is its use of the track-length estimator. This estimator capitalizes on the principle that at low photon energy, the dose is roughly equivalent to collision kerma, based on the assumption of charged particle equilibrium. Consequently, the track-length estimator can compute collision kerma and, in turn, the dose, D, by:

$$D_j = K_{col}^{j} = \frac{\sum_i E_i T_i \left(\frac{\mu en}{\rho}\right)_i}{V_j}$$

where Ei = energy photon traversing voxel, V_j = voxel volume, and t_i = tracklength of a photon through voxel, and $\left(\frac{\mu en}{\rho}\right)$ = the mass energy absorption coefficient for energy. The use of the track-length estimator saves time and computing power [31].

Furthermore, egs_brachy possesses a distinctive characteristic that enables users to select between normal and superimposed simulation modes. The normal mode simulates all source locations concurrently, thereby considering the impacts of interseed attenuation. In contrast, the superposition mode permits only one seed to be active at any given moment, effectively disregarding interseed effects. This superposition mode is particularly advantageous for simulating HDR treatments or conditions akin to TG-43 [28].

2.4.5 Graphical User Interface of egs_brachy application

The egs_brachy Graphical User Interface (eb_gui) serves as a graphical interface that facilitates rapid access to the egs_brachy application. Users have the capability to construct virtual patient models utilizing CT images, which incorporate clinician-drawn contours

found in the structure file (RT structure), as well as established plans that include dwell positions and dwell times detailed in the plan file (RT plan). Tissue densities are derived from CT densities via Tissue Assignment Schemes (TAS) and CT calibration files. Additionally, eb_gui is equipped to analyze and export Dose Volume Histograms (DVH) and dose distribution, enabling users to efficiently assess and compare results [37]. The figure 2.2 show the eb_gui interface. In this interface, the CT images and RT structure files were uploaded in the Import DICOM Virtual Patient Models.

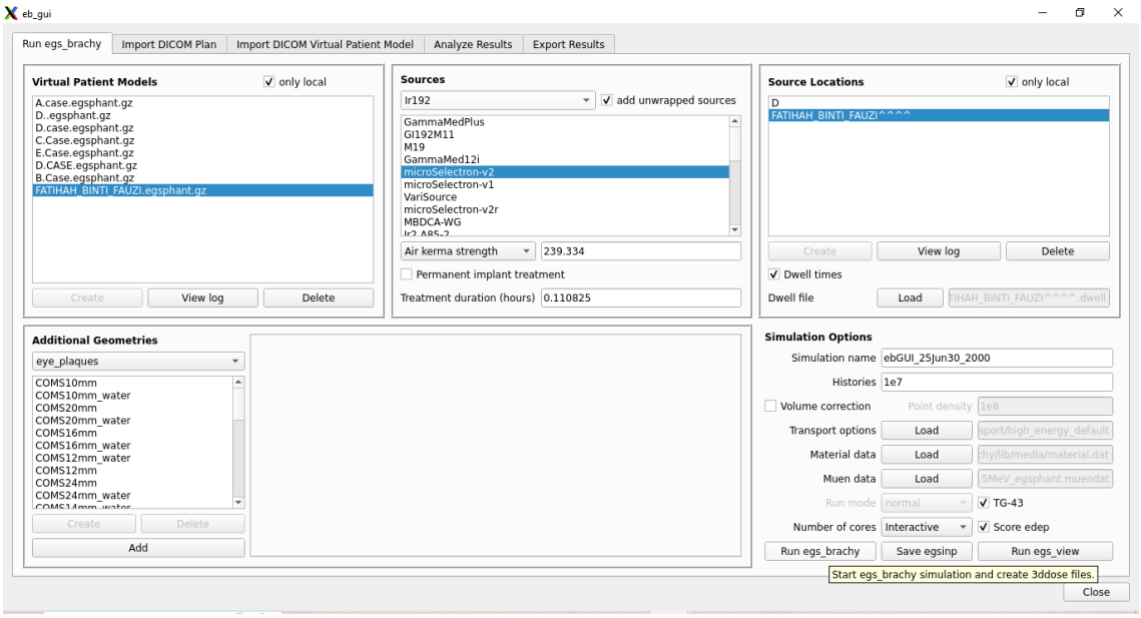

Figure 2-5: Graphical User Interface of egs_brachy application

2.4.6 Virtual Patient Model

The virtual patient model (VPM) created by eb_gui uses the three DICOM inputs alongside look-up tables to assign materials to voxels of the model [37]. The workflow for this creation process is displayed in figure 2.3

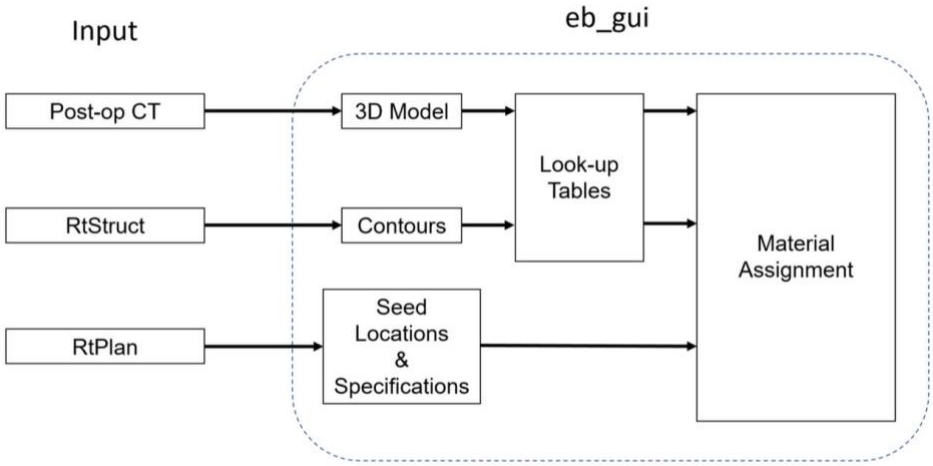

Figure 2-6: Workflow for eb_gui tissue assignment

The voxel resolution of the VPM is established based on the resolution of the CT images, which typically measure 512 x 512 x the number of slices in pixels. Each voxel is allocated a material type according to the CT number of the corresponding pixel and the designated structure of the voxel. For instance, in the case of a breast patient, the default tissue assignment would categorize the treatment area as generic female tissue, air, or cortical bone. Nevertheless, when the breast contour is present, the program assigns either adipose tissue, glandular tissue, or calcification instead. Similar assignment methodologies are applicable to specific contours, such as the ribs. In instances where voxels contain overlapping structural contours, it is essential to prioritize which structure the voxel will be assigned to [37]. A sample tissue priority chart, detailing the potential assigned tissues, is presented in Figure 2.4.

This material assignment based on CT numbers is capable of identifying and classifying calcifications within patients, a task that can be difficult to accomplish through visual inspection of CT scans.

Overlaying the voxel assignments are the brachytherapy seeds, which have specifications and material assignments derived from the RtPlan file. For example, the Pd-103 wrapped TheraSeed-200 consists of two graphite cores encased in a thin layer of palladium, separated by a lead spacer, and surrounded by air before being encapsulated in titanium [37]. Additionally, the seeds are enveloped in a thin layer of water within the program (though not physically present) to mitigate geometry errors that may occur due to the overlap of seeds with voxels. The eb_gui also facilitates the reduction of metallic artifacts

Breast	Prostate
CTV: adipose, gland, calcification	Urethra: urethra
ETV: adipose, gland, calcification	Prostate: prostate, P50C50, calcification
PTVs: adipose, gland, calcification	Rectum: rectum
Skin: skin, air	Bladder: bladder
Breast: adipose, gland, calcification	others: male soft tissue, cortical bone, air
Heart: heart	
Lung: lung, air	
Ribs: cortical bone, red marrow, yellow marrow	
Chest: adipose, muscle, cortical bone, cartilage	
Body: female soft tissue, air, cortical bone	
others: female soft tissue, air, cortical bone	

Figure 2-7: Sample contour priorities, with higher contours taking a higher priority in tissue assignment alongside possible assigned tissues

around the seeds, this reduces shadowing artifacts that would otherwise affect tissue assignments based on CT number [37]. A sample breast patient VPM is shown in Figure 2.5.

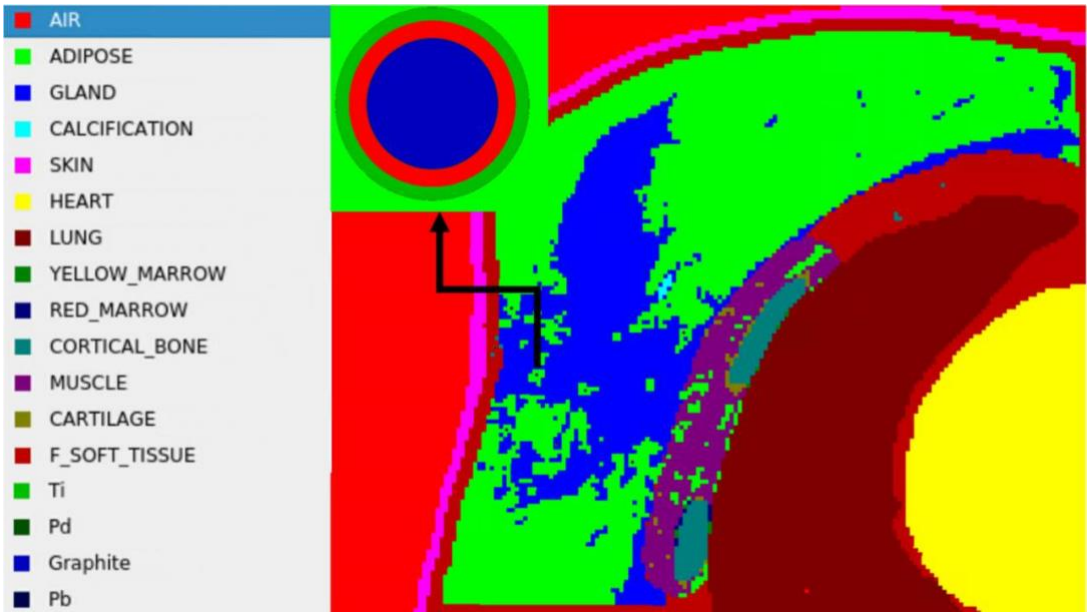

Figure 2-8: Sample breast patient VPM highlighting material assignment, a superimposed Pd-103 seed is shown in large to highlight seed material assignment

2.5 Validated of the dosimetric parameters of the BEBIG high dose rate (HDR) Ir-192 source (Ir2.A85-2) through Monte Carlo simulations

The GATE simulation code used for modeling the HDR Ir-192 source for the purpose of calculating its dosimetric parameters has been described in this article. In the study, the source geometry was modeled correctly inside a spherical water phantom with air and stainless steel materials, which resemble the actual design of the source. The dose rate constant, radial dose function , and the anisotropy function were also calculated. The dose rate constant was arrived at by evaluating the dose at a given distance from the source as the source developed a cone shaped radiation pattern while the radial dose function compared the change in dose as a function of distance from the source. Anisotropy was measured at various angles and distances in order to define alterations of dose distribution in three-dimensional coordinate system. The value for the dose rate constant for the BEBIG HDR