A COMPARATIVE STUDY OF PENCIL BEAM AND COLLAPSED CONE CONVOLUTION DOSE CALCULATION ALGORITHMS IN PELVIC AND THORACIC TREATMENT PLANS.

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A Research Project submitted in Partial fulfillment of the requirements for the Degree of Master of Science in Medical Physics

in

The School of Physics and Earth Sciences

of

The Technical University of Kenya

(November 2023)

DECLARATION

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

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DEDICATION

“I dedicate this research to my mother, whose aspirations have found expression through my endeavors. I am a living manifestation of her dreams”

ACKNOWLEDGEMENT

I would like to begin by expressing my deepest gratitude to God, whose guidance and grace have been my source of strength throughout this academic journey. I extend my sincere appreciation to my supervisors, who have guided me throughout this journey. This research is a culmination of divine guidance, institutional support, personal dedication, and the collective encouragement of those around me. I am profoundly grateful for the role each entity has played in the realization of this academic achievement.

ABSTRACT

Different algorithms used to calculate doses in radiotherapy planning adopt different techniques in simulating doses received by the target (tumor) volume. Such differences can come about in terms of dose distribution in the target volume and doses received by surrounding organs. Due to such differences, it is necessary to take into consideration the best algorithm suitable for a range of mediums i.e homogeneous and heterogeneous mediums. The differences in the way different algorithms simulate doses in different media may bring about dosimetric variations which can relatively affect treatment outcomes in 3D-conformal radiotherapy.

The primary focus of this research was to compare dose variations for two dose calculations algorithms namely, Pencil Beam (PB) algorithm and the Collapsed Cone Convolution (CCC) in highly and less heterogeneous mediums. The study was an analytical retrospective study consisting of 8 pelvic and 7 thoracic treatment plans approved and scheduled to undergo 3D-CRT. The treatment plans were generated using PB and the same treatment plans recalculated using the CCC calculation algorithm. Dosimetric variations between the two dose calculation algorithms were observed and evaluated based on variations in plan parameters such as dose received by the tumor volume and the dose received by critical organs (OAR's). Minimum and Maximum mean dose values were obtained from PTV and OAR's from the two dose calculation algorithms. Differences in dose values between the two algorithms were analyzed using standard errors (SE) to determine if in fact the differences were significant. At a CI of 95% (P=0.05), it was found out that the two calculation algorithms demonstrated insignificant dose differences to a treatment plan. PB algorithm demonstrated high dose received to the tumor volume compared to the CCC algorithm. A visual analysis of the results using box plots demonstrated that the two algorithms showed no major differences in doses received by the PTV and OAR's. It made no significant difference to a treatment plan if the planner (Medical Physicist) would adopt either of the algorithms in calculating doses for cervix or esophagus treatment plans using ONCENTRA Treatment Planning System.

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3D CRT	Three Dimensional, Conformal Radiation Therapy
AAA	Anisotropic Analytical Algorithm
ALARA	As Low As Reasonably Achievable
BEVs	Beam eye Views
CCC	Collapsed Cone Convolution
CT	Computerized Tomography
CTV	Clinical Target Volume
CI(95%)	Confidence Interval of 95%
DRRs	Digitally Reconstructed Radiographs
DVH	Dose-Volume Histogram
EBRT	External Beam Radiation Therapy
EPID	Electronic Portal Imaging Detector
GTV	Gross Target Volume
HI	Heterogeneity Index
IMRT	Intensity Modulated Radiation Therapy
LINAC	Linear Accelerator
MC	Monte-Carlo
MLCs	Multi-leaf Collimators
MRI	Magnetic Resonance Imaging
OARs	Organs at Risk
PB	Pencil Beam
PET	Positron Emission Tomography
PTV	Planned Target/Tumor Volume
QUANTEC	Quantitative Analysis of Normal Tissue Effects in the Clinic
TERMA	Total Energy Released per Unit Mass
TPS	Treatment Planning System
VMAT	Volumetric Modulated Arc Therapy

CHAPTER 1: INTRODUCTION

1.1: Background of Radiation Therapy

A remarkable progress towards treatment and management of cancer has been made possible through radiation therapy (Salimi *et al*., 2017). Gianfaldon *et al*. (2017) assert that radiation therapy in conjunction with other treatment modalities have been an effective method in treating cancer for over 100 years now. Radiation therapy involves the delivery of ionizing radiation in order to destroy or kill cancerous cells. Radiation therapy exists in two major types namely; internal and external beam radiation therapy (Salimi *et al*., 2017). External beam radiation therapy involves administration of high energy radiation outside the body to where the cancerous tumor is located. Internal radiation therapy on the other hand, uses radioactive sources which are sealed in catheters or through seeds to the location of the tumor. The radioactive sources can be in solid or liquid form. Brachytherapy is an example of internal radiotherapy where the radioactive source is placed in and near the tumor through the aid of applicators (Gianfaldoni *et al*., 2017).

The idea behind radiation therapy is to ensure that tumorous cells get destroyed by very high energy radiation such as photons and electrons. Radiation therapy works best if 100 percent of the prescribed dose is received by 100 percent volume of the cancerous cells or tumor (Salimi *et al*., 2017). There continues to be rapid progress in the field of radiotherapy boosted by several advances in imaging modalities such as the CT simulator and computerized system planning systems which make tumor visualization and localization very effective. Effective radiation treatment focuses on ensuring that maximum dose is delivered to the whole tumor volume and that there is little exposure to normal cells and organs near the tumor or cancerous cells. The

doses received by surrounding healthy organs should be As Low As Reasonably Achievable (ALARA principle). Normal cells can be able to quickly recover when exposed to radiation compared to cancerous cells (Basker *et al*., 2012).

The advancement of technology has made it possible such that there are more effective radiotherapy methods adopted in external beam therapy. According to Koka *et al*. (2022), planning procedures in external radiotherapy have become more accurate and effective through External Beam Radiation Treatment (EBRT) technologies such as three dimensional conformal radiotherapy also known as 3D-CRT, arc therapy, intensity modulated radiation therapy abbreviated as (IMRT), and volumetric modulated arc therapy (VMAT). These modalities are largely adopted in radiotherapy centers across the world for treatment and management of various types and stages of cancers. The modalities employed ensure that there is increased dose distribution to the tumor, there is better organ and volume delineation and normal tissues are spared from irradiation toxicity (Koka *et al*., 2022). According to Basker *et al*. (2012), more advanced imaging technologies such as the CT simulator, computer planning systems and treatment delivery equipment such as the Linear accelerator (LINAC) have helped in ensuring radiation therapy and treatment is effective.

1.2: Overview of Treatment Planning Systems (TPS) used in Radiotherapy.

In the various modalities of radiation therapy, patient treatment is designed using treatment planning systems which are in general, the heart of radiotherapy. Optimization of treatment plans for best possible treatment outcomes can be done using a treatment planning system. Through treatment planning systems, various factors and elements such as the tumor volume, placement of beams, beam intensities (beam weighting), dose distribution and doses received by surrounding organs can be assessed and evaluated. Treatment planning systems (TPS)

are a vital component in both internal and external beam radiotherapy. Through a treatment planning system, the medical physicist ensures that the tumor volume receives the maximum prescribed dose and organs surrounding the tumor volume are spared from radiation toxicity or receive radiation doses that are within tolerable levels as described in QUANTEC. The Quantitative Analysis of Normal Tissue Effects in the Clinic (QUANTEC) is a tool that summarizes normal tissue toxicity dose data sets/constraints that guide the planner to avoid deterministic and stochastic radiation effects to the patients after treatment (see Table 1.1).

Table 1:1 A Table of Quantec Dose Constraints as obtained from ONCENTRA

Dose Constraints Dose-volume constraints	
PTV1 (50 Gy)	$V_{95\%}$ (47.5 Gy) > 95 %
	D_{max} (0.1 cc) < 107 % (53.5 Gy)
PTV2 (60 Gy)	$V_{95\%}$ (57 Gy) > 95 %
	D_{max} (0.1 cc) < 107 % (64.2 Gy)
Lung	Mean dose < 20 Gy
	V_{20Gy} < 25 %
Heart	Mean dose < 25 Gy
	V_{30Gy} < 45 %[a]
	V_{40Gy} < 30 %[b]
CordPRV	D_{max} (0.1 cc) < 40 Gy (45 Gy permitted)
Liver	V_{30Gy} < 60 %
Individual Kidneys	V_{20Gy} < 25 %
StomachIn[c]	Max dose < 60Gy
StomachOut[c]	Max dose < 45Gy

[a]Applies only to $50Gy_{RA}$ and $60Gy_{RA}$ plans
[b]Applies only to $50Gy_{3D}$ plans
[c]Applies only to $60Gy_{RA}$ plans

The process of treatment planning involves a series of processes that ensures reliable dose distribution outcomes and the treatment plan is executable prior treatment (Clements *et al*., 2018). Three dimensional (3D) images of the patient's anatomy have made it possible to view

dose distributions when directly imposed on the patient's anatomy. According to Clements *et al*., (2018), treatment planning systems allow for the radiation oncologist, and the medical physicist to assess the treatment plan through BEVs (Beam eye views) and DVHs (Dose Volume Histograms) prior treatment.

Clements *et al*. (2018) asserts that treatment planning systems help in navigating through parameters such as beam placement to avoid irradiating critical structures of the human body. This may also include programming of multi-leaf collimators, collimator jaws, and the placement of compensators and beam modifiers such as the motorized wedge and bolus (Clements *et al*., 2018). These treatment planning systems adopt various dose calculation algorithms and optimization tools to provide for better treatment plans to be used in 3D CRT, IMRT and VMAT. An example of a treatment planning systems provided by the Varian Medical Systems, Inc. is Eclipse (see Fig 1.2).

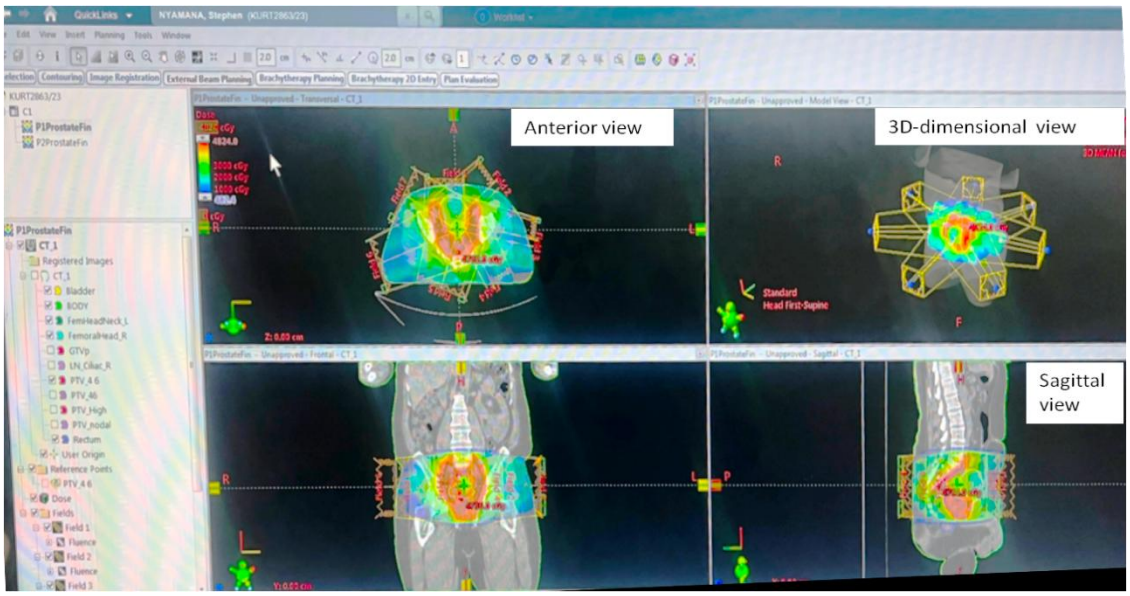

Figure 1.2: An Image of The Eclipse Treatment Planning System

The other treatment planning system is Monaco which is also designed to work with various manufacturers. Clements *et al*. (2018) describes that when Monaco is used with Elekta linear accelerator, the treatment planning system proves various exclusive features which can enhance quality of the final treatment plan. Such features include virtual leaf width, adaptive planning and smart sequencing. The Oncentra TPS is the other planning system for the Elekta linear accelerator that offers a variety of smart features and tools needed to optimize patient treatment plans. The planning allows the users to create, edit or modify the planning templates which have all the parameters needed to plan. Some of which include options for the arrangement of beams, dose prescription parameters, information on dose objectives for both the tumor volume and the Organs at Risk, isodose and dose-volume histograms display parameters (Clements *et al*., 2018). Figure 1.3 and 1.4 demonstrates the beam placement for a brain tumor case done on a treatment planning system. The beam arrangement for this case is two laterally opposing fields as demonstrated.

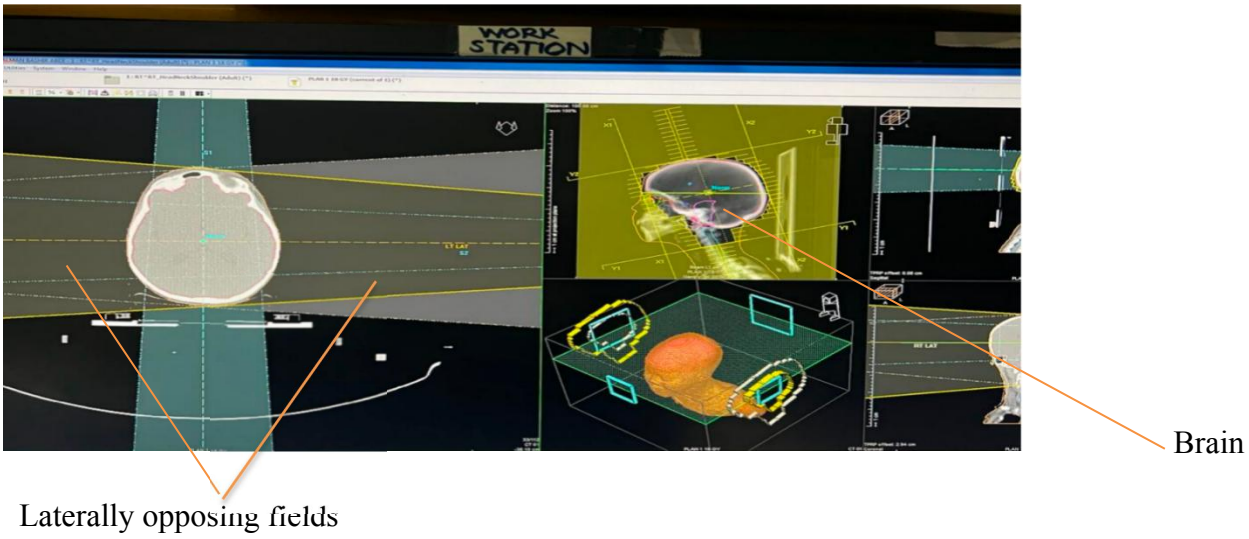

Figure 1.3: Brain Treatment Plan obtained from ONCENTRA

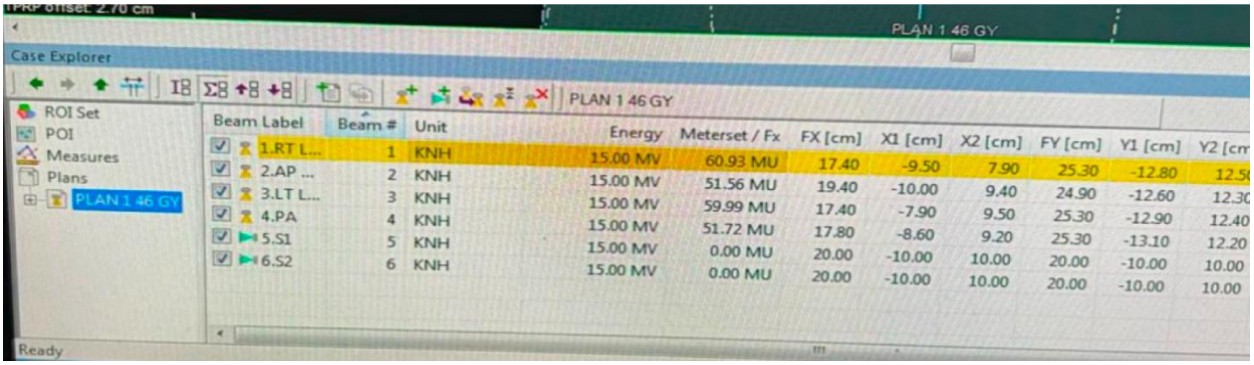

Figure 1.4: Beam Placement Process on 3D images obtained from ONCENTRA

Treatment planning systems used in radiotherapy have evolved from 2D to 3D display. Hegi *et al*. (2017) describes early radiotherapy planning systems relied on 2-Dimensional simulation and planning techniques to localize the tumor as well as beam placement or arrangement. A major disadvantage of 2-D radiotherapy planning was that visualization was restricted to include existing imaging (2D) planes making treatment less effective. The other disadvantage of 2D was that beam shaping and shielding proved difficult due to the unavailability of multi-leaf collimators (Hegi *et al*., 2017).

An open field technique is one of the most common beam arrangements used in 2-D planning. The technique involves placement of laterally opposing beams to the target volume. One of the major disadvantages of this technique is that it allows for higher doses to be received by surrounding healthy organs. Advances in technology have led to more advanced treatment planning system capabilities such as organ shielding through collimator jaws and multi-leaf collimators (MLCs) incorporated in the LINAC.

Diagnostic imaging technologies such as the CT, MRI, PET and combinational PET-CT have also contributed to improved radiotherapy treatment planning through creation of three-dimensional images of the patient's anatomical structures. Therefore the patient's scanned

images can be viewed from various planes i.e frontal plane, sagittal plane during treatment planning. The existing 3-dimensional planning systems have the power to superimpose beams directly on 3-dimensional images allowing for a technique known as the beam eye view to be able to visualize the radiation beam or the dose distribution on the tumor volume (Hegi *et al*., 2017). This is made possible through the construction and visualization of digitally reconstructed radiographs (DRRs) in radiotherapy treatment planning. Such advanced tools in treatment planning systems help in improving both efficiency and the accuracy of radiation therapy compared to 2-Dimensional treatment planning systems.

1.3: Dosimetry and Dose Calculation Algorithms

Accurate dosimetry is crucial in treatment planning particularly in ensuring that the planned target volume is receiving maximum dose while also minimizing doses received to critical surrounding healthy organs. Dosimetry in treatment planning focuses on calculation of radiation doses received by the patient during treatment. According to Rivera-Montalvo (2014), the dosimetric goal behind patient treatment is based on two main components namely verifying the dose delivered to patient and verifying patient positioning. Verifying patient positioning has been aided by imaging systems such as electronic portal imaging detector (EPID). On the other hand, verifying doses delivered to patients focuses on comparing measured and calculated doses distributions received by the target volume and organs at risk. Dosimetric differences can come about due to the adoption of different dose calculation algorithms (Rivera-Montalvo, 2014).

Modern radiotherapy modalities utilize dose calculation algorithms needed in calculation of accurate doses to ensure effective dose distribution to the target/tumor volume. De Martino et el. (2021) describes that one of the major challenges of modern radiotherapy is the ability to attain accurate dose distribution to the target volume within a short time. De Martino *et al*.,

(2021) describes that dose calculation algorithms adopted in radiotherapy treatment planning allow for the modeling of energy deposition patterns induced from a radiation source i.e linear accelerator (LINAC) in patient's anatomy made possible by electron density from a CT.

Different dose calculation algorithms adopt various techniques that simulate various interactions of radiation with matter. Photon interaction with matter depends on three key factors namely the photon energy, the atomic number and the medium density through which photon interaction occurs. The major photon interaction types are photoelectric effect, pair production and Compton scattering. In both pair production and Compton scattering, beam is attenuated such that there is a linear attenuation coefficient u (E) which comes about as a result of the sum of single attenuation coefficients (De Martino *et al*., 2021).

The evolution of 3D dose calculation models have allowed for better and even more accurate dose distribution and energy deposition models executable within clinical timelines.For example, some dose calculation algorithms assume that patient tissue is homogeneous or uniform in terms of density, whereas other dose calculation algorithms take into consideration heterogeneity of tissues such as tissues near the thoracic cavity consisting of air and bones. These algorithms can be used to simulate doses received in various mediums. However, due to differences in dose simulation and photon interaction techniques and difference in medium densities, variations in calculated doses may arise. If there are indeed dosimetric differences, are they of great significance and what are the impacts on the treatment plans or treatment outcomes?

According to Buzdar *et al*. (2010), the widely adopted analytical algorithms are pencil beam algorithm (PB), Anisotropic Analytical Algorithm (AAA), collapsed cone convolution algorithm (CCC) and Monte-Carlo (MC) simulations. Analytical calculation algorithms can calculate doses received by the target volume and critical organs based on two factors namely

the radiation beam and patient's anatomy (De Martino *et al*., 2021). Monte Carlo algorithms work by stimulating and understanding the behavior of photons as they interact with the patient's anatomy.

A major advantage of Monte Carlo algorithms compared to other algorithms is that they are more accurate and precise however, are computationally intensive compared to analytical algorithms such as pencil beam (De Martino *et al*., 2021). Monte Carlo algorithms have a longer computational time due to accuracy needed in calculating doses and thus fail to meet clinically acceptable timelines. Hybrid algorithms are another form of dose calculation such that they combine both Monte Carlo and analytical algorithms. Acuros XB algorithm is an example of a hybrid algorithm. De Martino *et al*. (2021) describes that the algorithm utilizes the pencil beam model to first calculate dose distribution in the target volume and later adopts the Monte Carlo simulation which accounts for differences in heterogeneity which may be difficult when using the pencil beam algorithm alone.

Calculations of doses have evolved from 2D models to 3D Monte Carlo simulations that predict radiation doses reaching the tumor volume and tissues and organs surrounding it. These dose-calculation algorithms allow for the correct representation of doses received by the patient by making sure that prescribed dose is received by the target and radiation received by healthy tissues/organs is minimized (Buzdar *et al*., 2010). For this reason, dose calculation algorithms are subject to research.

1.4: Pencil Beam (PB) and Collapsed Cone Convolution (CCC) Calculation Algorithms.

Dose calculation algorithms are of key importance in treatment planning as they form the basis of optimizing generated treatment plans (Kim *et al*., 2020). The existing calculation algorithms are categorized into three major groups based on their adopted mechanism of dose

calculation. These are factor-based calculation algorithms, model-based algorithms and principle-based dose calculation mechanisms. Factor-based calculation algorithms work by interpolation or extrapolation of doses from calculated measurements. Kim *et al*. (2020) assert that factor-based dose calculation algorithms are commonly used in situations where the heterogeneity correction is insignificant. An example of this algorithm is the Clarkson method of calculating doses.

The widely incorporated algorithms found in the majority of treatment planning systems (TPS) are the model-based calculation algorithms.The pencil beam algorithm and collapsed cone convolution are examples of model-based algorithms as depicted in figure 1.5.

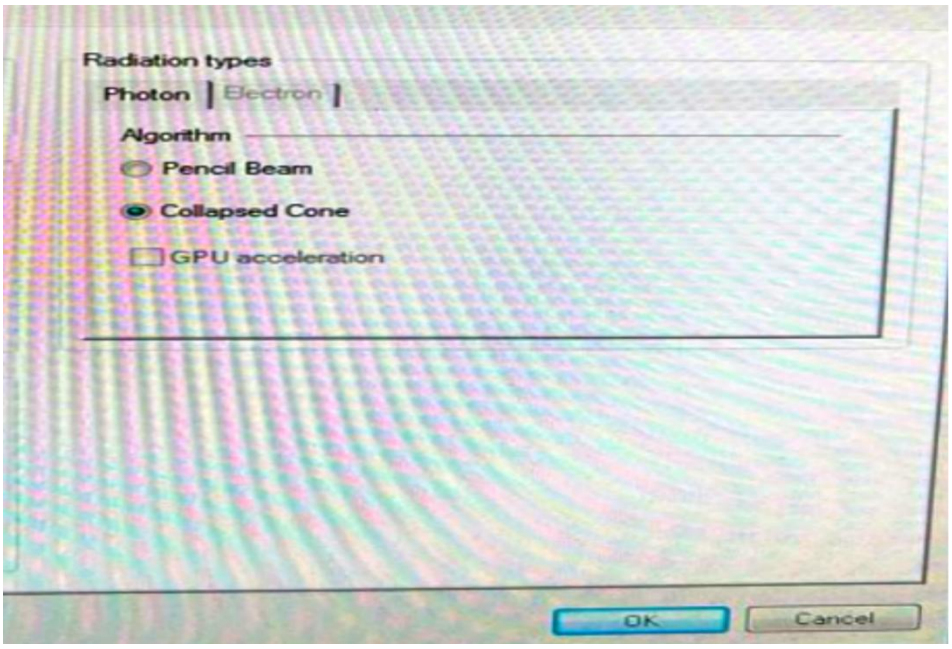

Figure 1.5: Oncentra Treatment Planning System Algorlithms (PB and CCC)

The other common model-based algorithms are the analytical anisotropic algorithms (AAA). The AAA algorithm is a type of improved Pencil Beam which adopts multiple PB dose kernels to be able to determine the dose contribution from a radiation source (Tajaldeen *et al*.,

2019). Model-based algorithms calculate dose distributions by the use of convolution equations which convolve photon energy fluence with a kernel (Kim *et al*., 2020). These algorithms are more precise in terms of dose calculation as they take into consideration the side scattering when beams are transmitted to a medium, an important aspect when calculating doses in heterogeneous medium (Kim *et al*., 2020). Monte Carlo calculations is an example of principle-based dose calculation algorithms such that it allows for the simulation of real processes of beam particle interactions with mediums. They provide more accurate dose calculations however may be time-consuming.

Model-based dose calculation algorithms adopt two key components. One refers to the TERMA denoted as Total Energy Released per Unit Mass. It represents total energy that is released to the medium/patient through photon interaction emerging from a Linear Accelerator. At the point of interaction of the photons, the TERMA can be given by the following equation:

$$\text{TERMA}=T(\vec{r}')=\frac{\mu}{\rho}(\vec{r}')\cdot\Psi(\vec{r}') \quad \text{..... 1.1}$$

where μ is the linear photon absorption coefficient,

ρ represents the density of the medium and

ψ represents energy fluence of the photons (primary).

The kernel is the second component which signifies the energy deposited by the scattering photons or electrons at the interaction site (Kim *et al*.,2020). According to Kim *et al*. (2020), a kernel represents the spread of energy which comes about as a result of photon interaction at a point or line (see Fig 1.6). Energy spread often happens due to existence of scatter photons which carry energy far away from the point of primary interaction. For example, the Pencil Beam algorithm uses a simple line kernel in modeling dose deposition when

transporting energy from the source to the patient. One of the challenges of the PB algorithm is that it fails to modify doses deposited based on changes in the medium density.

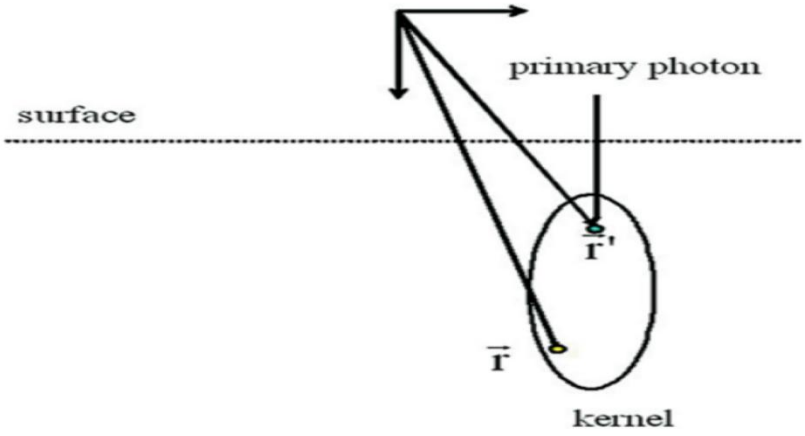

Figure 1.6: Point of interaction and kernel of the PB algorithm.

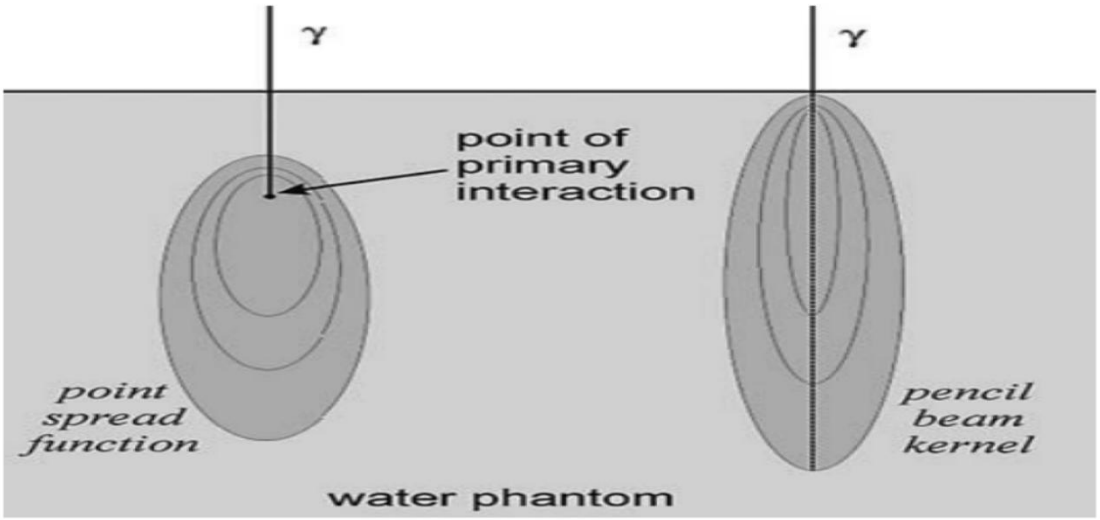

Figure 1.7: Point of interaction and PB kernel (Basker *et al*., 2012)

Model-based dose calculation algorithms calculate doses through the process of convolution of the TERMA and the KERNEL (Oelkfe & Scholz, 2006).

TERMA*KERNEL=DOSE.

This is referred to as the superimposition method such that the dose D (r), from a point, can be calculated by combining TERMA and the dose contributions from all the kernels k(r, E), of the existing energy spectrum, E (Oelkfe & Scholz, 2006). The equation can be represented as in equation 1.2.

$$\mathbf{D}(\vec{r}) = \int dE' \int d^3r' T(\vec{r}', E') k(\vec{r}', E'), \quad \text{.....1.2}$$

Due to complexity of computational power of these calculations, a much more accurate dose calculation can be achieved by narrowing the kernel into a distance function of the interaction points (r) and the point of interest (r') represented by equation below:

$$\mathbf{D}(\vec{r}) = \int dE' \int d^3r' T(\vec{r}', E') k([\vec{r} - \vec{r}'], E'), \quad \text{..... 1.3}$$

Despite that both PB and CCC algorithms are model-based algorithms, they differ when it comes to medium scattering. Differences between PB algorithm and CCC calculation algorithms in terms of accuracy largely depends on how the kernels of the two algorithms can simulate scattering especially in heterogeneous medium (Kim *et al*., 2020). The pencil beam kernel calculation algorithm presents a 3-dimensional dose distribution or scattering of a narrow mono-energetic beam in a homogeneous medium/water (Oelkfe & Scholz, 2006). The algorithm assumes the point of photon interaction with the medium occurs at the central axis of the beam and thus lateral scattering is homogeneous. Therefore, the inhomogeneity correction using the pencil beam is in the longitudinal direction.

Zhou *et al*. (2013) asserts that the CCC algorithm uses poly-energetic kernels from a beam spectrum originating from mono-energetic kernels thus the CCC algorithm is as a result sampling of dose kernels. The collapsed cone algorithm considers the inhomogeneity correction in both longitudinal and lateral directions. The CCC algorithm assumes that the interaction point is at a set of directed lines that are spread out in 3D (Kim *et al*., 2020). For each of the line, the CCC algorithm considers to be the axis of the cone. The CCC differs from the PB such that the kernels of each of the generated lines represents the energy that is deposited to the cone (see Fig 1.8)

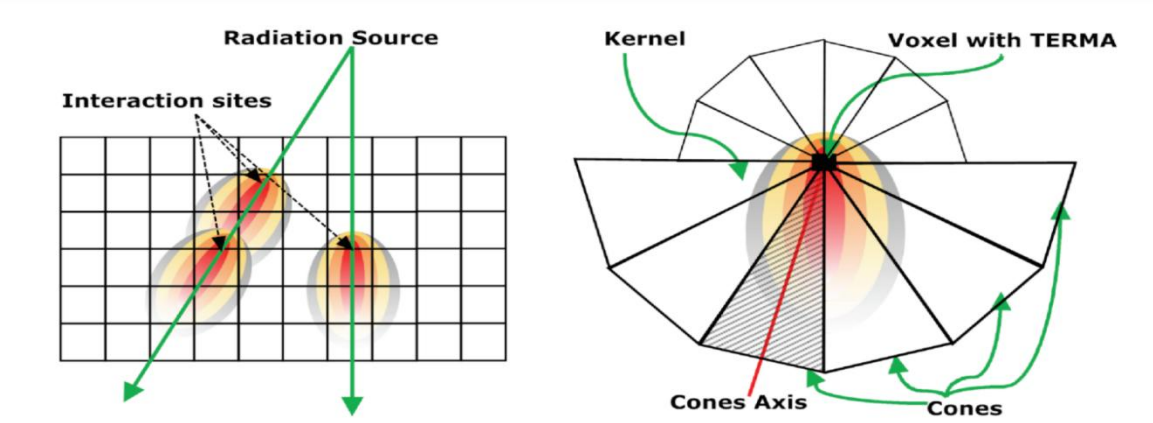

Figure 1.8: Point of interaction and kernel spread in CCC algorithm (Basker *et al*., 2012)

Kim *et al*. (2020) asserts that model-based calculation algorithms prove to be more accurate compared to factor-based algorithms however, they base their calculations on energy absorption and energy transfer processes which vary in different media. Due to such differences, it is necessary to analyze the behavior of dose calculation algorithms in highly heterogeneous and homogeneous mediums which is key in optimization of treatment plans (Zhou *et al*., 2013)

1.5: Statement of the Problem.

A major factor of consideration when calculating doses is the choice of calculation algorithm depending on the targeted region. At the Institution of study, only one algorithm was used to calculate doses for all clinical cases despite the ONCENTRA treatment planning system having both calculation algorithms; the Pencil Beam (PB) and Collapsed Cone Convolution (CCC). The study therefore questions and compares the behaviour of both algorithms in both highly heterogeneous (thoracic) and homogeneous (pelvic) mediums.

1.6: Justification/Significance of Study

A comparative study between PB and CCC allows for evaluation and assessment of the simulation techniques of the algorithms in different media/clinical cases. Evaluation of the two calculation algorithms can help to provide insights into dose calculations done by each of the algorithms and allows the planner to decide on which algorithm provides for minimal radiation toxicity to normal tissues or organs and allows for maximum tumor irradiation for various clinical cases. Ultimately, a comparative analysis between the calculation algorithms allows for quality assurance of treatment plans such that the chosen algorithm is best for specific clinical cases leading to quality treatment plans and improved treatment outcomes. In terms of clinical relevance, some of the prevalent cancers in Kenya are pelvic and thoracic-related cancers (Patel *et al*., 2013). A dosimetric comparison study can help to evaluate or establish dose calculation algorithms suitable for cervix and esophagus cancer cases (homogenous and highly heterogeneous medium) respectively.

1.7: Research Objectives

1.7.1 Broad Objective

To assess and compare calculated dosimetric variations between pencil beam and collapsed cone convolution dose calculation algorithms in highly heterogeneous and homogeneous mediums in 3D-conformal radiation therapy.

1.7.2: Specific Objectives

i. To quantify calculated dosimetric variations of two dose calculation algorithms on pelvic and thoracic treatment plans performed by the ONCENTRA 3D-CRT treatment planning system.

ii. To compare dose-volume outcomes of pelvic and thoracic treatment plans calculated by the two dose calculation algorithms through dose distribution differences in the planned target volume (PTV).

iii. To analyze and compare doses received by critical organs as a result of dose calculations made by the two calculation algorithms with reference to Qualitative Analysis of Normal Tissue Effects in the Clinic (QUANTEC)

1.8. Research Questions

i. Are there calculated dosimetric difference in calculated doses between Pencil Beam and Collapsed Cone Convolution in different media? If there are, are they of great significance to the treatment plan or treatment outcomes?

ii. What are the impacts of dosimetric differences to the Planned Target Volume and doses received by OAR's ?

1.9 Hypothesis

i. There are dose dosimetric differences between PB and CCC due to different techniques of simulation of photon interaction in different media.

ii. Dosimetric differences between the two algorithms can affect treatment outcomes depending on doses received by the target volume and surrounding healthy tissues.

CHAPTER 2: LITERATURE REVIEW

2.1: Introduction

Model-based dose calculation algorithms have been subject to extensive research work. These algorithms simulate photon interaction through convolution of photon energies with dose kernels, a process known as superposition. Pencil Beam and Collapsed Cone Convolution are the most common model-based algorithms adopted in most treatment planning systems. The two have different techniques when photons interact with a medium. The pencil beam dose calculation algorithm is such that energy spread or the dose kernel at a specific point in the medium is summed up to form a line or a pencil type of dose distribution (Buzdar *et al*., 2010). Pencil beam calculates dose distribution using a convolution technique such that mono energetic beams convolve with photon energy fluence. On the other hand, the collapsed cone model-based algorithm uses a convolution technique between the TERMA and the dose kernel. Because of this convolution, collapsed cone are able to calculate doses of various interfaces such as tissue-air or tissue-bone. Due to the different calculation or simulation mechanisms, the choice of algorithm can relatively influence treatment outcome and thus clinical implications based on the case. Kim *et al*. (2015) asserts that accurate dose calculations by dose calculation algorithms is key in achieving maximum tumor irradiation and sparing of normal tissues. Dose calculation algorithms tend to show major differences in dose calculation and distribution in heterogeneous media particularly since there is loss of electronic equilibrium in heterogeneous medium compared to homogeneous medium.

2.2 Interactive Techniques of Dose Calculation Algorithms

In a study to compare PB, CCC and MC calculation algorithms, Kim *et al*. (2015), observed that there are significant changes in the absorption and the scattering of beams in

heterogeneous medium. The study also highlighted that when PB was adopted in a heterogeneous medium, the calculated dose appears to be overestimated in comparison to other dose calculation algorithms. The PB algorithm did not explain the way in which electrons spread out in heterogeneous medium. The issues of electron transport especially in low-density areas (heterogeneous medium) have led to the conclusion that Monte-Carlo (MC) algorithms are more suitable in such clinical cases. The accuracy needed when using MC algorithms require very long calculation time which may not be convenient in a clinical setup. Because of this, the widely used modern calculation algorithms are Pencil Beam and convolution algorithms such as the collapsed cone convolution. The fast calculation time of the two algorithms makes it easy to study their interactive techniques in highly heterogeneous and homogeneous mediums.

It is also possible to study the limitations of these algorithms. Kim *et al*. (2015) describes that when it comes to PB, one of its major limitations is that it only utilizes a one dimensional kind of density correction and thus makes it quite impossible to accurately calculate doses in media with different electron densities. A comparison of the two dose calculation algorithms done by Elcim *et al*. (2016) for head, neck and chest wall cases, indicated that when calculating doses using PB algorithm, the point dose values were higher compared to when the doses were recalculated using CCC calculation algorithm. The study revealed that the PB dose calculation algorithm calculated less absorbed dose compared to CCC algorithm especially in areas where there were transitions in the medium (Highly heterogeneous). Bukulmez and Ozdemir (2021) explain that it can be quite challenging calculating doses especially in environments that are homogeneous mostly associated with air cavity, bone structures or areas with high density.

2.3 Effects of PB and CCC for Different Clinical Cases

The ICRU report 24 by Cunningham *et al*. (1976) indicates that dose calculation accuracy should not exceed 5% and if it falls between 2-3%, then it can have positive clinical implications. A study done by Bukulmez and Ozdemir (2021) focussed on finding out the effects of PB, CCC and Monte-Carlo calculation algorithms in esophagus cancer. Findings from the study indicated that PB algorithm gave good results in terms of dose distribution especially in homogeneous tissues or tissues with uniform density. However, a limitation of the algorithm was found that it did not take account for secondary distribution of electrons particularly in highly heterogeneous areas or areas with different densities. The algorithm demonstrated an overestimation of doses particularly at the low-density tissue areas and at the lateral interface of the target volume or the tumor (Bukulmez and Ozdemir, 2021). Bukulmez and Ozdemir (2021) asserts that there are difficulties that arise when calculating doses in inhomogeneous surroundings/media which are caused by either lung cavity, areas with bone structures or high density mediums. In most cases, an ideal dose calculation algorithm should be able to clearly simulate or reflect dose distribution received by the planned target volume (PTV) and the critical organs therefore reducing uncertainty especially during plan evaluation and plan approval.

Bukulmez and Ozdemir (2021) studied the impact of Monte-Carlo, PB and CCC when calculating doses for the esophagus to assess dosimetric differences that may arise in a heterogeneous environment. The study focussed on the middle esophagus as the tumor location as it is highly heterogeneous particularly because it is near the spinal cord, the heart and the costa vertebra. During contouring, these organs were contoured/ delineated as critical organs or organs at risk.The treatment plans used the same target and Organs at Risk contoured for all the plans to make sure that there was effective comparison. In all the treatment plans, the dose that was

prescribed was 50.4Gy such that a daily dose of 1.8Gy would be delivered for 28 sessions or fractions. The study investigated a total of 18 esophageal plans where energies used varied from (6-18MV) and a total of three fields used with angles (120, 90 and 72 degrees) for all the treatment plans. The plans were investigated using PB, CCC and Monte Carlo calculation algorithms.

Evaluation of the treatment plans utilized D50, D98 and D2 for the doses received by the Target Volume (PTV), V30 for evaluation of heart dose and mean dose, V20 for the lung dose and Dmax was used to evaluate doses received by the spinal cord for all plans calculated by PB and recalculated by MC and CCC.

where D50= Dose received by 50% of the target volume

D98=Dose received by 98% of the target volume

D2= Dose received by 2% of the target volume

V20= Volume of the organ receiving 20Gy.

Dmax= Maximum dose received by the target volume.

The study also compared the Homogeneity Index (HI) for all treatment plans calculated using the three algorithms. The HI is an analysis tool that evaluates dose distribution in the planned target volume (PTV). The Monaco planning system was used in planning. It is a TPS developed by Elekta company. With Monaco, the system allows the planner to choose the calculation algorithm to be used. The TPS used various tools to optimize the plan such as the gantry angle, multi-leaf collimators and beam weighting.

Results from the study showed that the algorithms generated different outcomes for plans with the one energy and the same beam angles. The findings of the study also concluded that the Monte Carlo calculation algorithm showed better results particularly in terms of the volume

coverage and minimizing doses received by the surrounding tissues. The target coverage was assessed using Dmin values and the MC algorithm showed better results. The study also found out that higher dose values were observed especially when using Monte-Carlo. In terms of doses received by organs at risk, maximum dose values were observed when using the MC algorithm and showed the lowest when using Pencil Beam. Since the study focussed on esophageal cancer, mean doses (Dmean) for the heart and the lung were considered. The values were found to be high when using Monte Carlo and lowest when using PB. V30 and V5 values for the heart were lowest for the plans calculated using PB and were the highest when using Monte Carlo. V10 and V20 values for both lungs showed to be high with MC and lowest using the PB.

where V30=Volume of the organ that received 30Gy

V5=Volume of the organ that received 5Gy

V10=Volume of the organ that received 10Gy

V20=Volume of the organ that received 20Gy

The study compared the homogeneity index (HI) of the three calculation algorithms and it was found that the PB had the best homogeneity as the values obtained were much much less than one. According to Bukulmez and Ozdemir (2021), significant differences were seen in the doses received by the critical organs when calculating using the three algorithms. Due to such differences it was easier for the planner to decide on the algorithm to adopt when preparing treatment plans for esophageal cancer cases using various energies (6-18MV). From the study, it was evaluated that when it comes to giving acceptable results, Pencil Beam worked best in homogenous mediums or tissues with uniform density however one of its major limitations was that it failed to shape electron (secondary) distribution especially in mediums that are heterogeneous or areas with non-uniform densities. The algorithm overestimated doses that were

received at the lateral face of the target volume or the tumor and areas with low densities. On the other hand, the MC algorithm demonstrated better results in dose coverage to the target volume as it took account of the interaction processes in both homogenous and heterogenous mediums.

A study done to compare PB and CCC for lung treatment plans by Pearson *et al*. (2009) demonstrated that the dose distribution to the target (tumor) was better when using CCC.Pearson *et al*. (2009), noted that the CCC calculation algorithm showed better results in delivering 90% of the total prescribed dose to the target volume and showed better coverage/ distribution compared to PB. There was a significant difference when it came to the lung dose (V20) for plans recalculated using CCC. There was a reduction in the lung dose for all plans generated using collapsed cone compared to pencil beam. However, the monitor units or the mean absolute dose for the CCC was found to be 2-3% higher. According to Pearson *et al*. (2009), this has no major clinical significance in terms of doses received by normal tissues or the organs at risk. The study concluded that the dosimetric accuracy of the treatment plans generated using CCC were higher compared to those calculated using PB.

In another study by Koelbl et al. (2004), to compare the two calculation algorithms, for patients with lung cancer, the observation was that the dose value for the PTV was much lower when compared to PB. The study focussed on analyzing the influence of the algorithms particularly dose distribution to the PTV and the doses received by critical organs. Normalization of the lung treatment plans were followed with reference to ICRU report 50 by Wambersie *et al*. (1992) and the dose-volume histograms analyzed in terms of values of D max, D mean, D min and D median to respective volumes of interest. Findings from the research indicated that PB when used in lung cancer cases overestimated the doses especially at the boundary of the target volume. A major reason for this was suggested that when using PB, primary doses get calculated

without taking into consideration lateral inhomogeneities. One of the major consequences of this is that there is occurrence of lateral particle equilibrium however this is not the case for tumors that are located next to air cavities such as the lung cancer cases and most head and neck cases.

The PB overestimates the doses that are received in low density targets and at the laterals of the target volume or the tumor. The CCC algorithm showed better results especially in low density areas due to the nature of simulation with media. According to Koelbl *et al*. (2004), the point kernels from CCC form a series of coaxial cone-like beams that are of equal angles. The energy that's released to the respective cones is then rectinearly carried and deposited along the axis of the cones (collapsed to the cone axis). During the process of energy transportation, both absorption and attenuation processes are heightened by electron density. Therefore the CCC algorithm takes into consideration tissues inhomogeneities that exist in the volume that is being irradiated.The study thus concluded that when dealing with thoracic particularly lung cancer cases, PB would not be the best algorithm to use because it does not take account for lateral scattering of electrons and thus the CCC would be the best algorithm to use for calculating dose distribution.

Abdul *et al*. (2014) conducted a research study to investigate differences for various energies IMRT in prostate plans using PB and CCC. A total of 15 prostate plans were chosen and treatment planning done using Oncentra Master treatment planning system (version 4.3). The plans were generated taking into consideration the dose constraints for critical organs and a 95-107% dose uniformity of the Target Volume (PTV). For all the treatment plans, gantry angles ranging from (0,40,80,120,160, 200 and 280) degrees were selected. Dosimetric evaluation and quality of the treatment plans was done through assessment of homogeneity index (HI) and Conformity Index (CI) in accordance with the radiation therapy oncology group (RTOG).

Evaluation was also done by assessing the maximum, minimum and mean doses received by critical organs such as rectum, bladder and the femoral heads.

Assessment of doses was done using the Student's t-test sampling method with a P value < 0.05. The study found out that there were no major differences in terms of HI and CI of the two calculation algorithms. Analysis of doses received by organs at risk were analyzed with reference to QUANTEC. In both algorithms, it was observed that for higher energies (15MV) there were much better dosimetric conformities. Lower doses received by the bladder and the rectum were also observed with higher and mixed energies for both algorithms. The results from the study concluded that when using mixed energy IMRT (6 and 15 MV), collapsed cone showed better results when optimizing treatment plans compared to PB algorithm. For all plans,there was no major dosimetric difference between the algorithms on dose reduction for Organs at Risk. The table 2.1 summarizes max and min doses the CTV received in both calculation algorithms. It also shows a comparison of HI and CI in both.

Table 2.1: HI and CI Comparison for Different Energies (Abdul *et al*., 2014)

		CCC		
	6 MV	15 MV (Mean ± SD)	Mixed energy	*P*
CTVmin	70.56 ± 3.16	69.02 ± 1.71	71.04 ± 2.09	<0.043
CTVmax	90.97 ± 2.04	88.71 ± 3.01	90.05 ± 1.8	<0.05
CI	1.212 ± 0.04	1.129 ± 0.05	1.253 ± 0.03	<0.06
HI	1.189 ± 0.02	1.160 ± 0.02	1.177 ± 0.03	<0.056
		(b)		
		PB		
	6 MV	15 MV (Mean ± SD)	Mixed energy	*P*
CTVmin	74.94 ± 3.02	70.21 ± 2.21	72.76 ± 2.54	<0.061
CTVmax	92.74 ± 2.1	90.31 ± 3.67	91.55 ± 3.09	<0.047
CI	1.257 ± 0.05	1.210 ± 0.05	1.314 ± 0.04	<0.07
HI	1.2131 ± 0.03	1.181 ± 0.04	1.197 ± 0.04	<0.066

Kim *et al*. (2015) asserts that there are bound to be dosimetric differences when comparing calculation algorithms; MC, PB and CCC. In the research study, dosimetric differences among the three algorithms for a lower energy (6MV) in inhomogeneous regions were put to comparison. A maximum of 5 breast (chest wall) and 5 lung cancer cases were calculated using the three calculation algorithms. The results indicated that the MU calculated using PB were much lower compared to CCC. The MC algorithm demonstrated accurate dosimetry compared to the other two algorithms. PB overestimated doses received to the PTV compared to MC and CCC, however PB and CCC demonstrated acceptable coverage due to the adoption of optimization techniques. The table 2.2 illustrates a comparison of the dosimetric data received by the OAR's from the three algorithms.

Table 2.2: Dosimetric Data Obtained For Breast and Lung Cases (Abdul *et al*., 2014)

			PB	CC	MC	$P < 0.05^*$
Breast	Ipsilateral lung	[b]Mean (Gy)	11.92 ± 0.65	11.36 ± 0.72	10.06 ± 0.40	e2, e3
		[a]V_{5Gy} (%)	32.74 ± 3.81	35.24 ± 3.94	31.54 ± 3.17	-
		[a]V_{20Gy} (%)	22.64 ± 1.01	22.63 ± 1.08	20.05 ± 0.36	-
	Heart	[b]Mean (Gy)	12.48 ± 1.70	11.98 ± 1.78	8.21 ± 0.68	e2, e3
		[a]V_{5Gy} (%)	44.14 ± 5.91	41.61 ± 6.97	30.05 ± 3.49	e2, e3
		[a]V_{30Gy} (%)	16.21 ± 2.84	15.88 ± 2.84	9.78 ± 0.48	e2, e3
Lung	Rt. lung	[b]Mean (Gy)	28.94 ± 12.79	29.21 ± 12.54	28.83 ± 11.60	-
		[a]V_{5Gy} (%)	71.77 ± 21.61	75.71 ± 19.88	76.65 ± 20.05	-
		*V_{20Gy} (%)	58.57 ± 23.75	60.93 ± 22.63	61.17 ± 22.75	-
	Lt. lung	[b]Mean (Gy)	9.34 ± 2.23	9.42 ± 2.00	9.52 ± 1.91	-
		[a]V_{5Gy} (%)	70.75 ± 13.67	72.00 ± 13.51	72.65 ± 12.33	-
		[a]V_{20Gy} (%)	6.16 ± 4.81	5.87 ± 3.97	6.57 ± 6.57	-
	Heart	[b]Mean (Gy)	9.90 ± 7.69	9.65 ± 7.49	9.08 ± 6.50	-
		[a]V_{5Gy} (%)	51.97 ± 40.74	50.63 ± 40.66	52.48 ± 39.34	-
		[a]V_{30Gy} (%)	5.41 ± 6.34	4.88 ± 5.62	3.12 ± 3.85	-
	Trachea	[b]Mean (Gy)	22.16 ± 9.88	22.39 ± 9.28	23.62 ± 9.06	-
	Esophagus	[b]Mean (Gy)	23.45 ± 10.71	23.98 ± 10.30	23.46 ± 9.62	-
	Spinal cord	[c]Max (Gy)	46.56 ± 3.29	45.62 ± 3.87	42.65 ± 1.18	-

Where: Vx% represents volume that is receiving x percent of total prescribed dose

Mean is the mean doses received by the Organs at Risk.

Max is the maximum doses received by the critical organs.

There has been extensive research done comparing dosimetric differences between existing calculation algorithms with much focus on comparing Monte Carlo and the two model based algorithms; CCC and PB. There is however a need for extensive retrospective studies that compares dosimetric variations that may exist between CCC and PB in highly heterogeneous (inhomogeneous) and homogeneous treatment plans. If there are any dosimetric differences are they significant or do they have clinical implications to patient outcomes?

This research project will focus on comparing doses calculated using Pencil Beam and Collapsed Cone Covolution in highly heterogeneous regions and homogeneous regions. A major gap in literature is the behaviour of these algorithms in different medium and to assess if doses simulated by the two algorithms have an impact on a treatment plan and ultimately the patient treatment outcomes.

CHAPTER 3: METHODOLOGY

The following chapter outlines and discusses the methods used to compare dose differences between pencil beam and collapsed cone dose calculation algorithms in cervix and esophagus cancer treatment plans. This chapter presents the materials and methods, treatment planning information, experimental methods used and statistical analysis methods used to carry out this research study.

3.1 Materials and Methods

The study population in this research included a total of 15 treatment plans approved for 3D- conformal radiation therapy. Image acquisition was the first step of treatment planning. Patient anatomical data was acquired from the same computed tomography (CT) simulator and patient slices sent to the Digital Imaging and Communications in Medicine (DICOM) via a Compact Disc (CD) to the ONCENTRA TPS. All the acquired CT slices were of the same thickness (3mm thick). The study included a total of 7 Oesophageal cancer treatment plans under thoracic region and 8 cervix plans under pelvic area. The n number of cases chosen for esophagus (n=7) and cervix (n=8) was chosen based on the availability of the cases. In addition, most research done from the literature review demonstrates fewer sample size chosen for comparative studies between PB and CCC (Elcim et al., 2016). Staging of the cancer cases ranged from stage 1 to 4, with nodal involvement and metastasis.

3.2 Contouring

Contouring otherwise known as delineation was the second step of planning such that contours of the Gross Target Volume (GTV), the Clinical Target volume (CTV), the Planned

Target Volume (PTV) and the organs at risk (OAR's) were manually drawn on the acquired CT image from the Oncentra Treatment Planning System (See Fig 3.1)

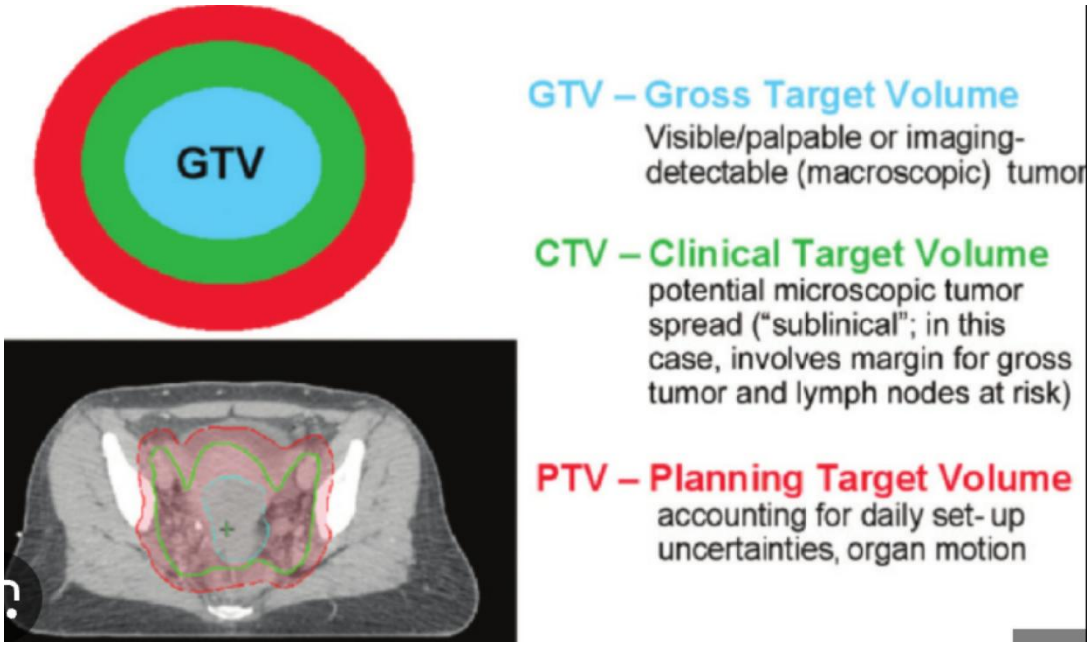

Figure 3.1: The GTV, CTV and PTV (Martinez *et al*., 2011)

Contouring ensured that there was a distinction of the target volume and the critical organs. The structure templates for each case was different with different organs at risk depending on the tumor site. For pelvic cases, the organs at risk taken into consideration were the bladder, and the rectum. On the other hand, for the esophagus, the organs at risk considered were the heart, the lungs, and the spinal cord. Delineation/contouring of the organs at risk were drawn using the RTOG-0815 protocol (Martinez *et al*. 2011)

3.3 Treatment Planning

The Oncentra planning system was used to generate plans using PB and CCC calculation algorithms. The TPS comes with the Elekta Version S Linear Accelerator with 6 and 15 MV photon energies and electron energies of 6, 9, 12 and 15 MeV. The energies used were 6MV for the esophagus cases and 15MV for cervix treatment plans. In some thoracic treatment plans (cases involving upper and mid-esophagus) doses were calculated using mixed energies for the various fields (6 and 15MV). The ONCENTRA TPS comes with various tools that allows for treatment planning such as placement of fields (Anterior-Posterior AP, Lateral Fields (LL and RR) fields, placement of gantry and collimator angle, energy, wedge, bolus, adjustment of multi-leaf collimators (MLC) and jaws, and various plan optimization features.

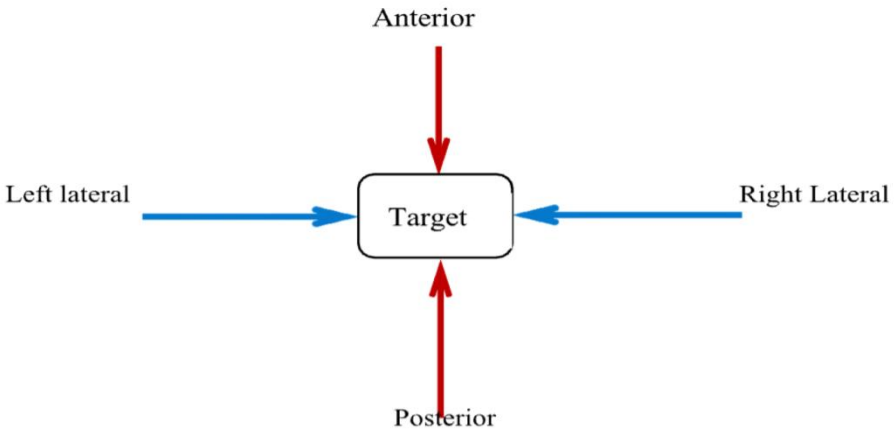

Figure 3.2 Lateral Fields (Four Box technique)

The plans were generated taking into account dose constraints and targets for planned target volume (PTV) and specific OAR's. Cervix treatment plans were generated using the four-field box technique for various field sizes and different weighting on all the field/beams (see Fig 3.2). The gantry angles used in cervix cases were 0,90,180 and 270 degrees. For esophagus

plans, beam angles varied depending on location of the target (upper or mid esophagus). Field angles ranged from oblique angles to lateral fields. All plans were calculated using the Pencil Beam algorithm and the same treatment plans recalculated using Collapsed Cone Convolution. Optimization was done taking into account the dose coverage/distribution in the planned target volume and doses received by the OARs for all treatment plans. Treatment plans were generated taking into consideration ICRU 50 report. In addition QUANTEC was used to evaluate doses received by OAR's.

3.4 Site of Study

The research study took place at one of the Cancer Treatment Centres in Kenya. The hospital is a public level 6 hospital and offers affordable health services to the general public. The hospital provides a range of cancer treatment services including chemotherapy, brachytherapy, palliative patient care and external beam radiation therapy (EBRT).

3.5 Experimental Methods

The research was a comparative experimental research design that attempted to establish dosimetric differences between PB and CCC used in radiotherapy treatment planning systems. Independent variables, in this case, the two dose calculation algorithms, were manipulated to evaluate their impacts on pelvic (cervix) and thoracic (esophagus) treatment plans.

3.6 Statistical Analysis of Data

Standard Errors (SE) was used to analyze and approximate standard deviations obtained from the sample population and comparing the obtained minimum and maximum mean values. Standard Errors were used as a measure of accuracy to compare pencil beam and collapsed cone convolution dose calculation algorithms. To get a coefficient estimate of maximum and

minimum mean values of each algorithm, the typical rule of thumb used was at a 95% confidence interval (P=0.05)

CHAPTER 4 : RESULTS, ANALYSIS AND DISCUSSION

This chapter presents the results and analysis of the research study after following experimental methods highlighted in Chapter 3. Table 4.1 gives a general summary of the planning information on the cases that were under study.

Table 4.1: Planning Information on Clinical Cases

Case	Number of cases (n)	Target Volume	OAR Constraints	Dose/Fraction	Beam Arrangement
Cervix	8	PTV 50Gy	Rectum (V50<50) Bladder (V65<50)	25 fractions (2Gy per fraction)	Four-Fields (Laterally opposing fields) (AP/PA LT & RT Lats)
Esophagus	7	PTV 41.4-50.04Gy	Lung (V20<20) Lungs Combined (V20<30) Heart (Mean Dose=26) Spinal Cord (Dmax=45)	20-25 fractions	Oblique angles and/or Laterally opposing beams

4.1 Results

Tables 4.2 to 4.4 presents the average (mean dose) dose received by the PTV for the all the cervix and all the esophagus cases under study. The tables also portrays results of doses received by OARs for all cervix and esophagus treatment plans. The means and standard deviations were calculated from average number of plans for all cervix (n=8) and esophagus (n=7) treatment plans.

Table 4.2: Dosimetric Data for PTV Coverage in all study cases

OAR's	**PB (Mean ± Standard Deviation)**	**CCC (Mean ± Standard Deviation)**
1. Cervix (PTV 50Gy)	47.12 ± **2.57**	46.64 ± **2.71**
2. esophagus	45.93 ± **2.88**	43.93± **3.15**

Table 4.3: Dosimetric Data for OAR's for Cervix Cases (Pelvic)

OAR's	**PB (Mean ± Standard Deviation)**	**CCC (Mean ± Standard Deviation)**
1. Rectum (D50<50%)	45.26 ± **6.54**	45.04 ± **6.27**
2. Bladder (D50<50%)	48.93 ± **2.12**	48.82 ± **2.27**

Table 4.4: Dosimetric Data for OAR's for esophagus Cases (Thoracic)

OAR's	**PB (Mean ± Standard Deviation)**	**CCC (Mean ± Standard Deviation**
1. Heart (Mean Dose<26)	19.18 ± 4.00	18.61 ± 3.80
2. Lungs Combined (Mean Dose (Mean Dose < 27)	20.33 ± 5.36	19.89 ± 5.12
3. Spinal Cord (Max Dose<45)	33.41± 10.89	32.58 ± 10.66

D50 : Volume of OAR receiving 50Gy of prescribed dose.

Average/Mean : The mean dose received by OARs

Max : The Maximum dose received by OARs

4.2 Data Analysis

Standard errors (see eqn 4.1) were calculated to analyze the differences in means values obtained from calculating doses using the two algorithms. The standard error of the means provided a statement of probability (p) regarding the differences in the mean doses of the sample size. The value for z* = 1.96 for a confidence level of 95% used, such that for all calculations the following formula was applied.

$$\text{Standard Error (SE)} = \text{Mean value} + z^* \frac{\text{Standard Deviation (SD)}}{\text{Square root of n (Where n= Sample Size)}} \quad \text{..... 4.1}$$

where z* is the value at a Confidentiality Level of 95% (P=0.05)

After applying equation 4.1 to raw data obtained from tables 4.2, results yielded maximum and minimum mean dose values for PTV cervix and PTV esophagus as demonstrated in tables 4.5 and 4.6. Similarly, equation 4.1 was applied to data obtained from cervix and esophagus OAR's (see tables 4.3 and 4.4) to obtain maximum dose values received by the cervix and esophagus organs at risk.

Table 4.5: Maximum and Minimum Mean Values for PTV Cervix

PTV (Cervix)	**Max Mean Value**	**Min Mean Value**
Pencil Beam	49.69	44.55
Collapsed Cone	49.35	43.93

A graphical representation of the maximum mean dose value for the dose received by both algorithms for PTV cervix and PTV esophagus is represented under the figures 4.1 and 4.2 respectively.

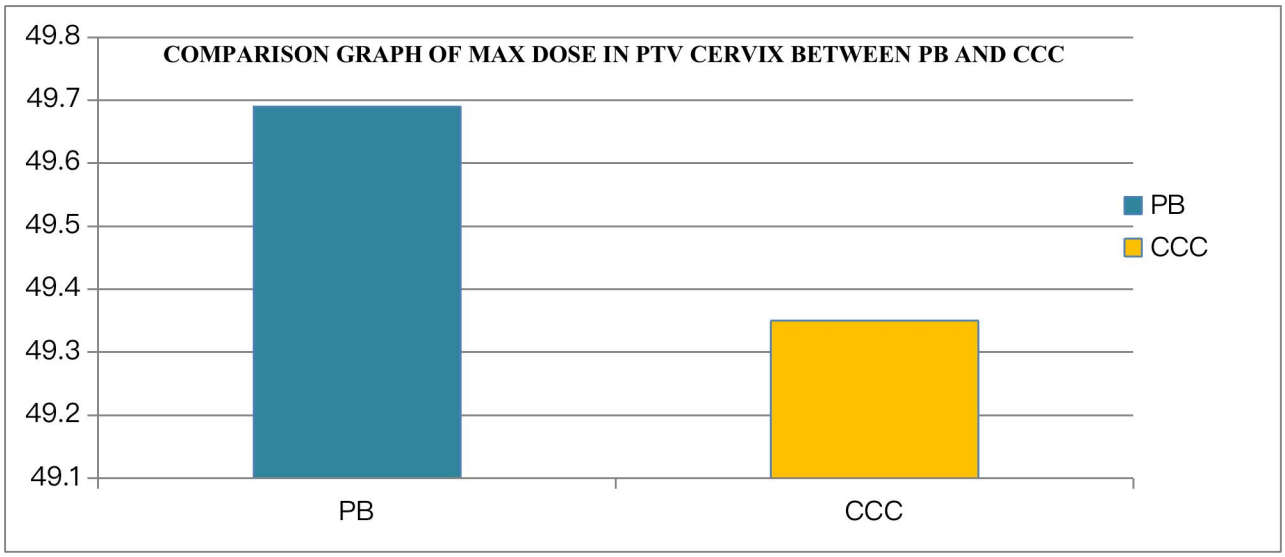

Figure 4.1: PTV Cervix Comparison Graph

4.3 PTV esophagus

Table 4.6: Maximum and Minimum Mean Values in PTV esophagus

PTV (esophagus)	Max Value	Min Value
Pencil Beam	48.81	43.05
Collapsed Cone	47.08	40.78

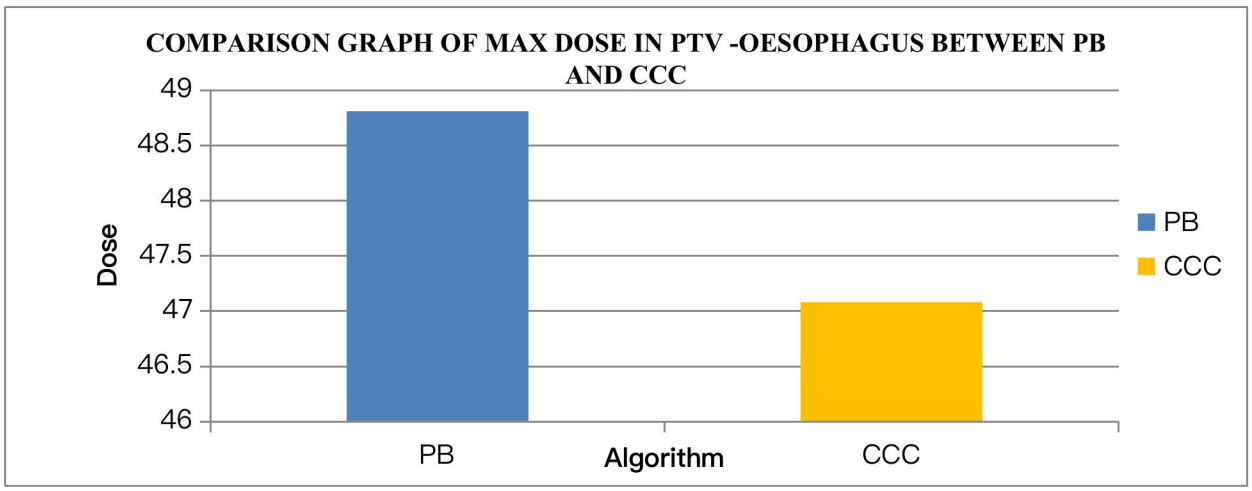

Figure 4.2: PTV esophagus Comparison Graph

In both pelvic and thoracic cases, PB demonstrated high dose coverage to the tumor/target volume compared to Pencil Beam. However, in both algorithms, at least 95% of the prescribed dose was received by the target volume (ICRU 50 recommended).

4.4 OAR Cervix

Tables 4.7 - 4.11 demonstrate the maximum and the minimum mean dose values for cervix and esophagus organs at risk. Similarly, Figures 4.3 - 4.6 represent maximum mean doses received for both cervix and esophagus organs at risk.

Table 4.7: Maximum and Minimum Mean Values for Rectum

Rectum	Max Mean Value	Min Mean Value
Pencil Beam	52.80	38.72
Collapsed Cone	51.31	38.77

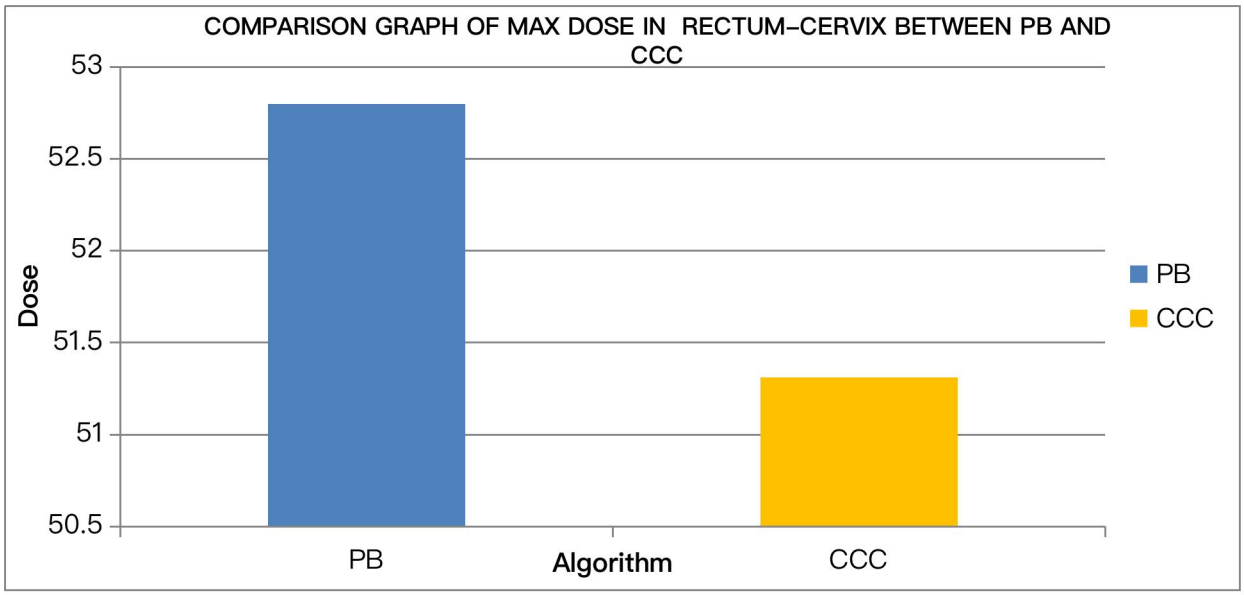

Figure 4.3: Comparison Graph of Max Rectal Dose

The comparison graph demonstrates that the maximum dose received by the rectum for all cervical cases was lower when using the CCC algorithm than the PB. Thus more organ sparring when calculating doses using CCC.

Table 4.8: Maximum and Minimum Mean Values for Bladder

Bladder	**Max Mean Value**	**Min Mean Value**
Pencil Beam	51.05	46.81
Collapsed Cone	51.09	46.55

In all cervical cases, the maximum dose received to the bladder was lower when using the PB algorithm compared to CCC.

4.5 OAR's esophagus

Table 4.9: Maximum and Minimum Mean Values for Heart

Heart	**Max Mean Value**	**Min Mean Value**
Pencil Beam	23.18	15.18
Collapsed Cone	22.41	14.81

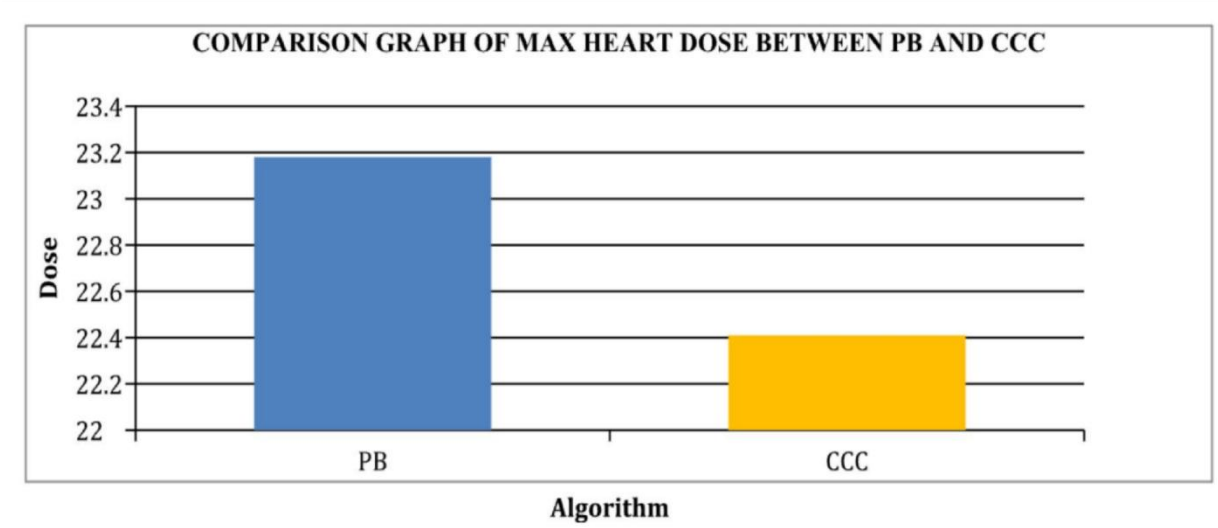

Figure 4.4: Heart Dose Comparison Graph

Table 4.10: Maximum and Minimum Mean Values for Lungs Combined.

Lungs Combined	Max Mean Value	Min Mean Value
Pencil Beam	25.69	14.17
Collapsed Cone	25.01	14.69

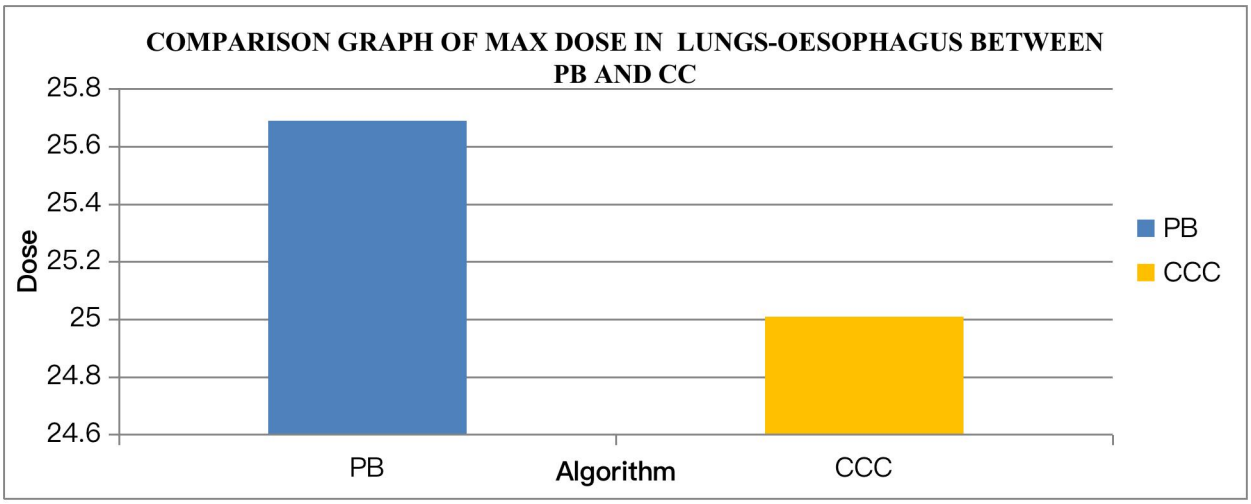

Figure 4.5: Graph of Max Dose for Lungs

Table 4.11: Maximum and Minimum Mean Values for Spinal Cord.

Spinal Cord	Max Mean Value	Min Mean Value
Pencil Beam	44.30	22.52
Collapsed Cone	43.24	21.92

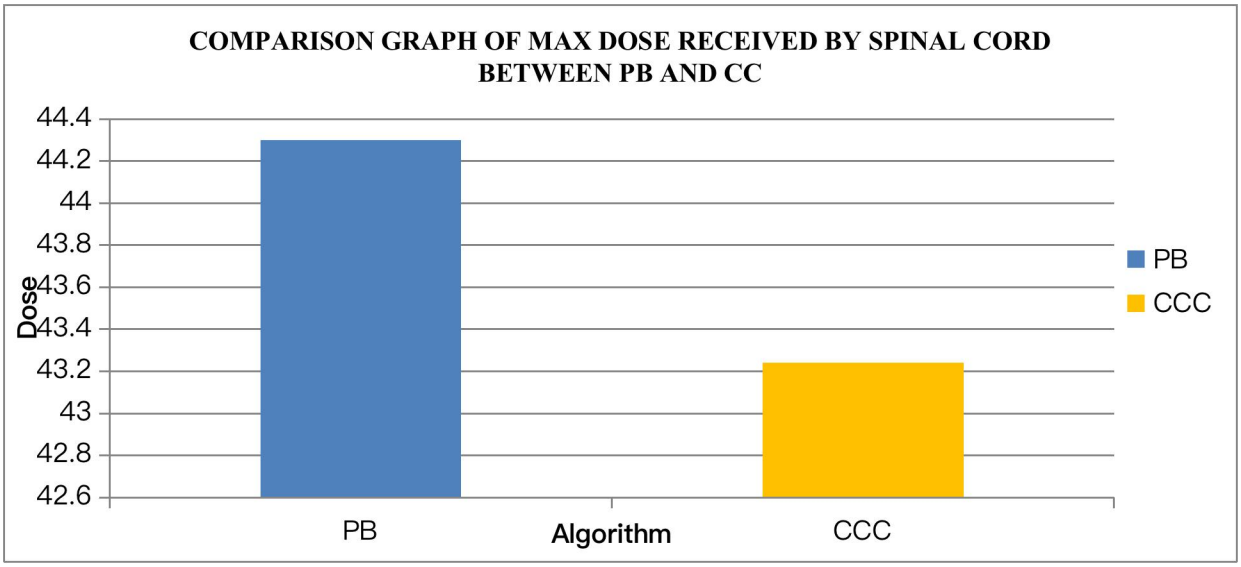

Figure 4.6: Comparison Graph of Spinal Cord Max Dose

For all esophagus OAR's, PB algorithm demonstrated high dose received to the lungs, heart and spinal cord compared to the CCC algorithm (see Fig 4.4- 4.6) . Despite that, the two algorithms however showed acceptable results in terms of doses received to the OAR's with reference to QUANTEC.

4.6 Discussion

Table 4.1 gives a summary of the planning information on the cases, target volume and dose constraints of the clinical cases analyzed in the research study. A total of 15 cases were analyzed to identify dosimetric differences between PB and CCC in different mediums. Eight Cervix cases and seven oesophageal cases under pelvic and thoracic regions respectively were chosen and planned following ICRU 50 radiotherapy planning guidelines and QUANTEC constraints for the OARs (Wambersie *et al*., 1992)

Table 4.2 summarizes PTV dose coverage for all the chosen cases. For all pelvic and thoracic cases, the two dose calculation algorithms showed acceptable results in terms of dose coverage to the target volume and compliance with ICRU Report 50 (95% of the dose prescribed should be received by the target volume). Table 4.3 and 4.4 shows doses received by OAR's when calculating doses using Pencil Beam and Collapsed Cone Convolution for Cervix and esophagus cases. Results of doses received by OARs in all algorithms showed acceptable doses as per the QUANTEC for all treatment plans.

Results from the study showed that there were indeed calculated dosimetric differences between pencil beam and collapsed cone convolution. PTV dose coverage however, was higher in the PB algorithm than for CCC algorithm for all study cases (see Tables 4.5 and 4.6). In both algorithms, there were healthy tissue sparring however, the CCC calculation algorithm demonstrated less doses received to the Organs at Risk (OAR's) which is attributed as a major advantage of CCC over PB as demonstrated in Tables 4.9, 4.10 and 4.11. Doses received by OARs and the target volume from the two algorithms showed no major significance and impact to treatment plans.

Kim *et al*. (2015) found out from a comparative study between PB and CCC, there were no significant differences in terms of dose coverage to the target volume (breast) however, PB demonstrated superiority over CCC in terms of more dose received to the target volume (95% of the prescribed dose). Results from the study by Kim *et al*. (2015) are in agreement with results obtained from this research study such that the PB algorithm demonstrated high dose coverage to the PTV for esophagus and cervix cases.High dose received to the target volume indicated that surrounding OAR's were bound to receive high doses as well. This was evident in doses received by the rectum, lungs, spinal cord and the heart when calculating doses using PB (see Fig 4.3, 4.4, 4.5 and 4.6) and vice versa was true. CCC showed relatively lower dose to the target volume but acceptable (at least 95% of prescribed dose) according to ICRU 50. In all clinical cases, the CCC algorithm demonstrated lower dose received by OAR's (see Tables 4.9, 4.10 and 4.11).

A major question examined in this research study was whether the differences in the two algorithms were significant to a treatment plan and the question of choice of calculation algorithm when calculating doses in mediums with different electronic equilibrium. Therefore, Box plots were used to help in visualizing the results obtained from the two algorithms categorized into PTV and OARs.

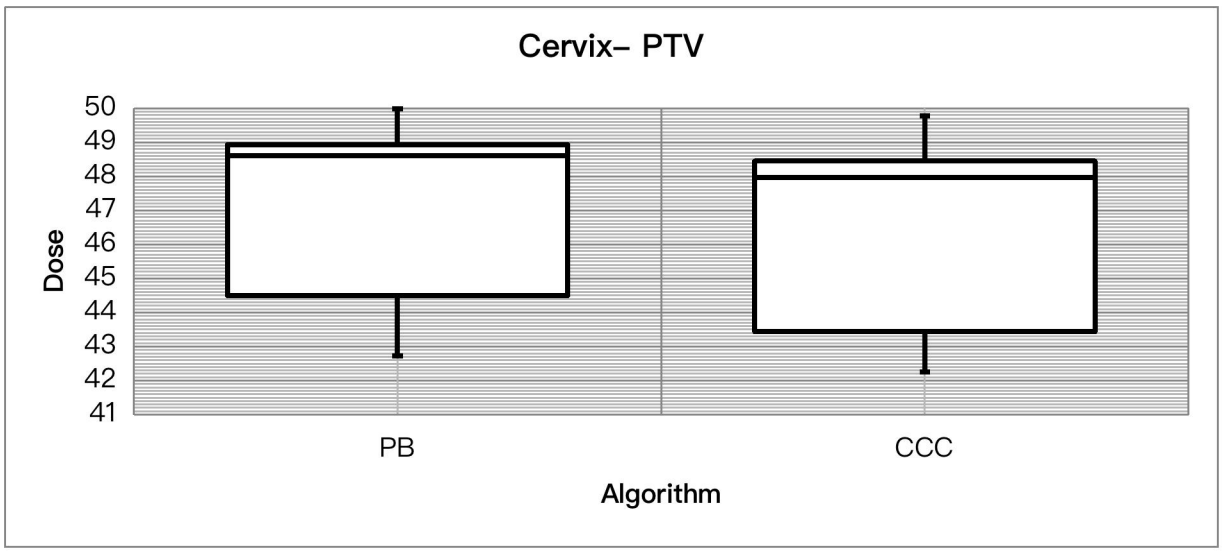

Figure 4.7: A Box Plot of PTV Cervix

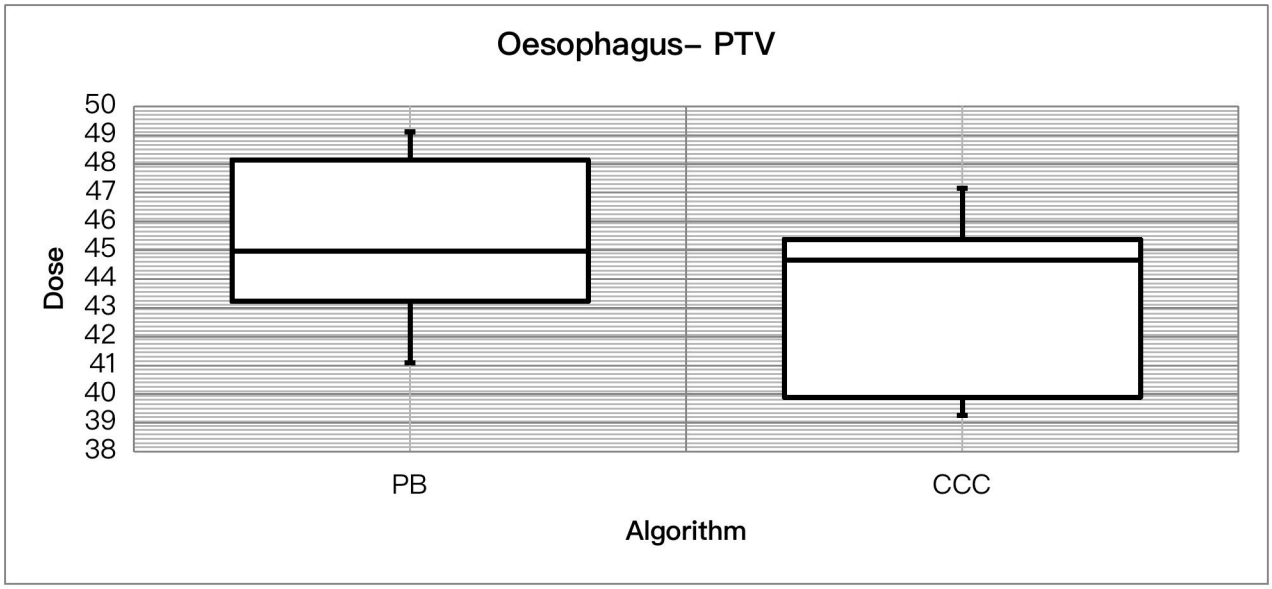

Figure 4.8: Box Plot of PTV esophagus

In both PTV's (cervix and esophagus), the two calculation algorithms showed no significant differences in terms of dose received to the tumor volume (see Figure 4.7 and Figure 4.8)

Box Plot of Cervix OAR's

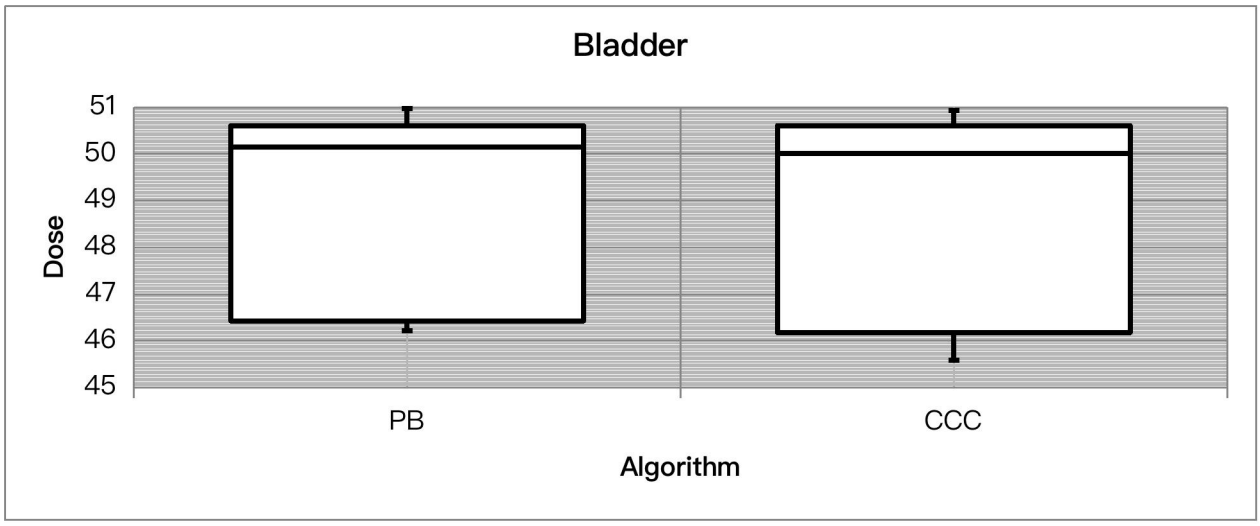

Figure 4.9: A Box Plot showing Bladder Dose in PB and CCC

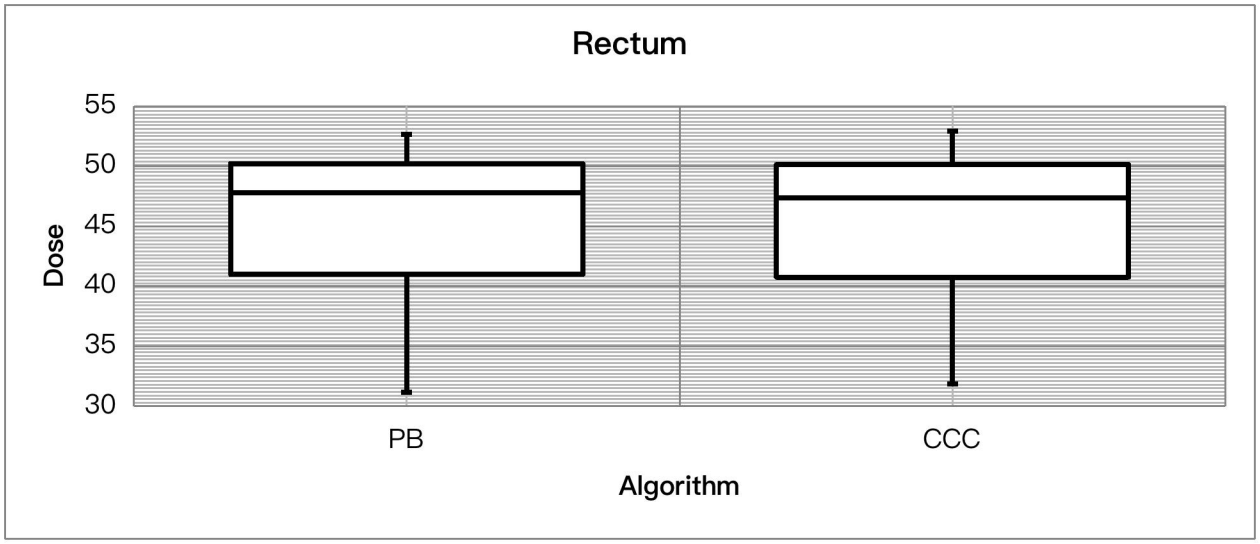

Figure 4.10: Box Plot of Rectal Dose in Both Algorithms

In both algorithms, PB and CCC showed no major significance difference in terms of doses received by the rectum and the bladder as demonstrated in Figure 4.9 and Figure 4.10.

Box Plot of esophagus OAR's

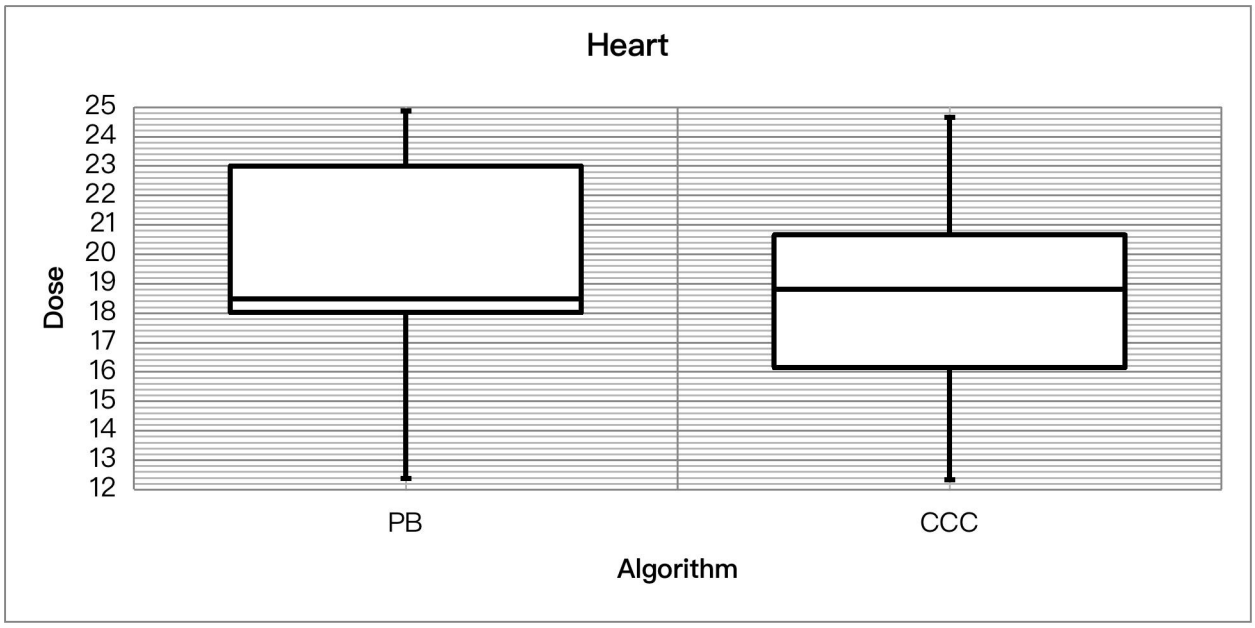

Figure 4.11: Box Plot depicting Heart Dose

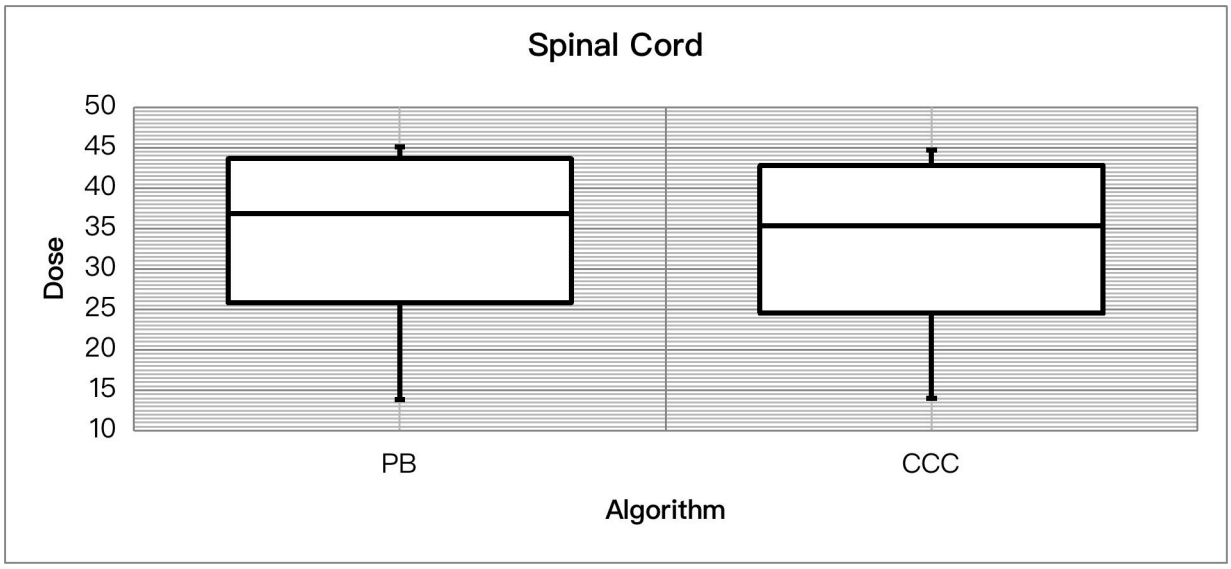

Figure 4.12: Box Plot showing Spinal Cord Dose

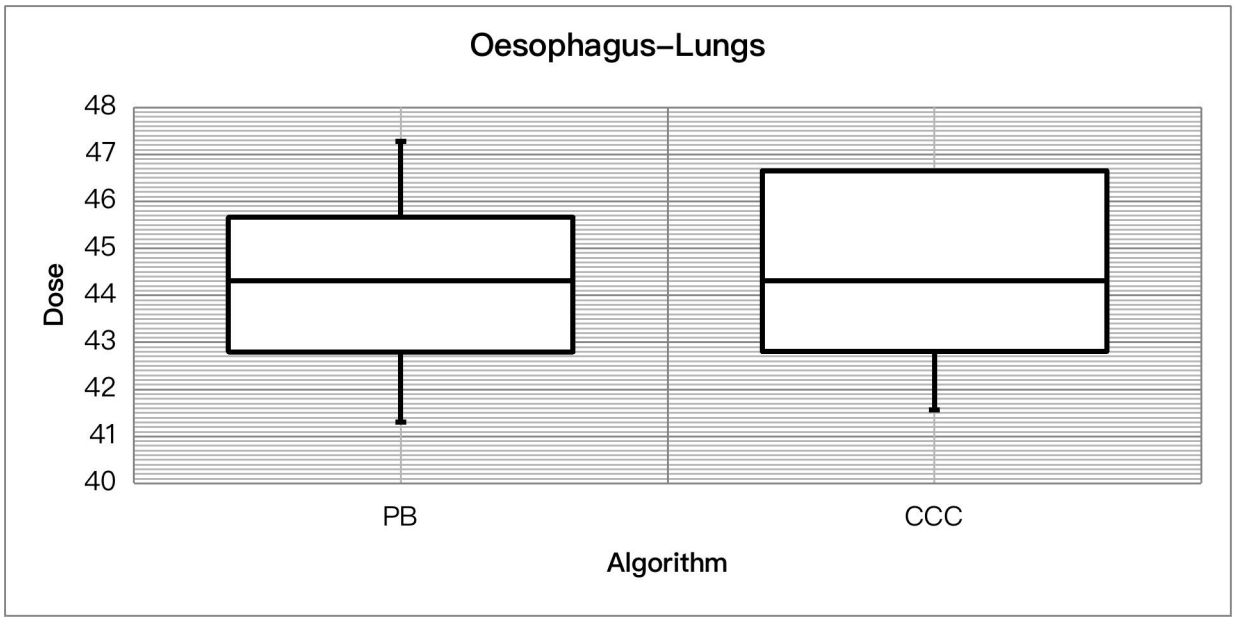

Figure 4.13: Box Plot showing Lung Dose in PB and CCC

The high dose coverage when using the PB algorithm especially in esophagus cases was attributed by an overestimation of dose particularly in the esophagus cases. Kim *et al*. (2015) concluded that PB overestimated dose in lung treatment plans and thus the monitor units needed to achieve optimal dose coverage to the planned target volume were less compared to CCC and Monte Carlo dose calculation algorithm.

From theory, the two algorithms have different methods of simulating doses to the target volume. A major factor contributing to such differences is the type of medium interaction. This research focused on esophagus (highly heterogeneous/ low density region) and cervix (highly homogeneous/ high density region). Pencil Beam considers one point of interaction and energy spread (kernel) from that point of interaction to the target volume. On the other hand, the CCC algorithm has various points of interaction through which energy spreads. Because of this, the two algorithms will simulate doses in different medium. The CCC is capable of accounting for both lateral and longitudinal energy transport and thus works best in mediums with different

electronic densities (breast and esophagus). Results from the present study found out that the CCC algorithm achieved better results in terms of dose received to OAR's in both esophagus and cervix cases. Although the PB algorithm was superior in dose coverage to the PTV, CCC also demonstrated acceptable results for dose received by the tumor volume as demonstrated in Figures 4.7 and 4.8

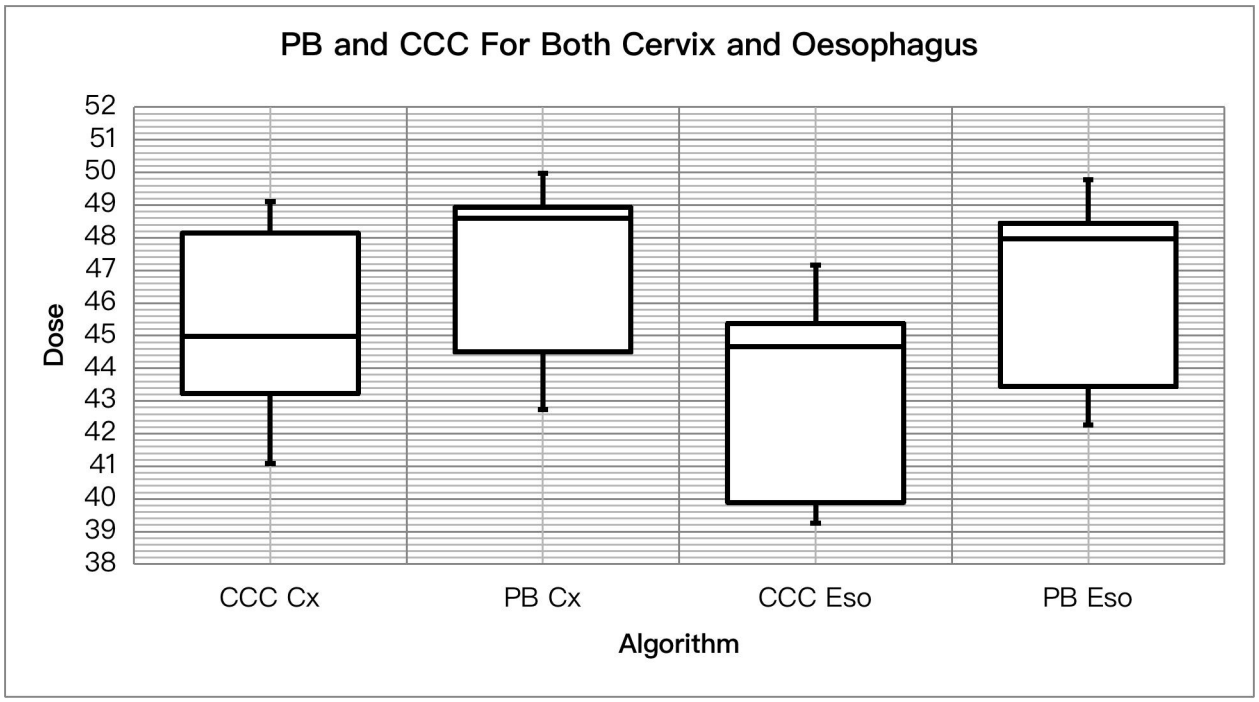

Figure 4.14:Box Plot showing Dose received by both Cervix and esophagus PTV

Where Cx=Cervix plans

Eso= Esophagus

The box plot above (Figure 4.14) indicates that for Cervix and Esophagus clinical cases, the PB algorithm showed higher dose coverage compared to CCC. In as much as PB showed superiority, the combined box plot depicts that there were no significant differences between the CCC and the PB algorithms in terms of dose received to the planned target volume (PTV).

These findings were also true for doses received by OAR's for both CCC and PB. The CCC algorithm demonstrated lesser dose received to surrounding organs compared to PB however, a visual representation of the two from box plots shows there were no significant differences between the two algorithms (see Figures- 4.13). The threshold for statistical significance applied was P=0.05 (CI of 95%).

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The two dose calculation algorithms demonstrated that there were indeed differences in doses received by the tumor volume (Planned Target Volume) and OAR's in different media. The PB algorithm showed high dose coverage to the target volume in both cervix and esophagus treatment plans thus showed superiority in dose received by the tumor volume. On the other hand, the CCC algorithm performed better in terms of doses received by surrounding organs.

The Pencil Beam algorithm demonstrated high dose received to the tumor volume or the PTV in both esophagus and cervix cases by 10%. Because of such differences, it would be easier to imply that treatment plans would be impacted and that one algorithm was superior to the other in terms of doses received to the tumor volume. Standard errors were calculated to analyze the the accuracy of the means values obtained from calculating doses using the two algorithms. In addition, box plots were used to visualize these differences and it was found that the differences in doses received by the tumor volume from the two calculation algorithms were insignificant and would not impact the generated treatment plans.

The Collapsed Cone Convolution algorithm demonstrated better results in terms of doses received by the surrounding healthy tissues compared to the Pencil Beam algorithm. The difference is doses was also 10% such that the CCC demonstrated lower doses received by critical organs. Despite such difference in doses, the Qualitative Analysis for Normal Tissues Effect in the Clinic (QUANTEC) demonstrated that both the Pencil beam algorithm and the Collapsed Cone Convolution showed acceptable results in terms of doses received by the surrounding Organs at Risk (OARs). In addition, the two aglorithms showed acceptable results according to ICRU report 50 despite such dosimetric differences.

Therefore, It made no significant difference to a treatment plan if the planner (Medical Physicist) would adopt either of the algorithms in calculating doses in heterogeneous or homogeneous medium. At 95% CI, the two algorithms showed no significant differences to the treatment plan despite the PB algorithm showing high dose to the target volume compared to pencil beam and CCC algorithm demonstrating much lower doses received by critical organs.

5.2 Recommendations

This research study focused on comparing dosimetric variations of the two dose calculation algorithms in cervix (pelvic) cases and esophagus (thoracic) cases. A major area of future research can be a comparative study of the two algorithms in highly heterogeneous mediums such as breast treatment plans.

There is also need for a comparative study of the two algorithms (PB and CCC) and Monte-Carlo algorithms in pelvic and thoracic treatment plans. It would not have been possible to compare the two algorithms with Monte-Carlo in this research since the Oncentra TPS only utilizes the PB and CCC algorithms. Future research can thus focus on comparing the three dose calculation algorithms in homogeneous and heterogeneous regions and to assess doses received by the tumor volume and surrounding OAR's.

5.3 Limitations

A major challenge encountered during this research was limited access to information regarding the ONCENTRA Treatment Planning System used in External Beam Radiation Therapy. Information regarding this system was only available for brachytherapy Treatment Planning System (TPS).

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APPENDICES

Appendix I

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ORIGINALITY REPORT

14%	9%	11%	4%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	"Scientific Abstracts and Sessions", Medical Physics, 2017 Publication	1%
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5	pore.unavco.org Internet Source	1%
6	pubmed.ncbi.nlm.nih.gov Internet Source	<1%
7	Submitted to Chester College of Higher Education Student Paper	<1%
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