COMPARISON OF TREATMENT INDICES BETWEEN TELECOBALT MACHINE AND LINEAR ACCELERATOR-BASED TREATMENT PLANS FOR SELECTED CONFORMAL RADIOTHERAPY CASES

BY

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DECLARATION

"This thesis is a result of a research work undertaken by Allan Mukonesheshe Kamfosi in the Department of Medical Physics, School of Nuclear and Allied Sciences, University of Ghana, under the supervision of Prof. A.W.K. Kyere, Mr. George F. Acquah and Mr. Samuel Nii Adu Tagoe."

I hereby affirm that except for references which have been cited, this work is a product of my own research and it has not been presented in part or whole for any other degree in this University or elsewhere.

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ABSTRACT

The use of telecobalt machine in radiotherapy is of concern in developing countries where there is a limited resource. As such, the study was to ascertain if telecobalt (cobalt-60) machine could be feasible to generate and deliver treatment plans with optimal treatment indices comparable to those of a linear accelerator (Linac).

Retrospective DICOM-Radiotherapy images of patients earmarked for treatment of breast, prostate and lung cancer obtained from the European Society for Radiotherapy and Oncology (ESTRO) were uploaded unto the treatment planning system (TPS) used by National Center for Radiotherapy and Nuclear Medicine (NCRNM) and Sweden Ghana Medical Center (SGMC Cancer Center). Based on departmental protocol, international dose constraints, careful selection and adjustments of beam parameters, treatment plans were generated and delivered. Thereafter, treatment indices were calculated and compared. The plans were also subjected to quality assurance to determine their adequacy for clinical implementation.

The results of conformity index (CI) were: breast (0.9705, 0.9303), prostate (0.9881, 0.9948), lung (0.9604, 1.0005) and for homogeneity index (HI) were: breast (1.1452, 1.0910), prostate (1.0226, 1.0141), lung (1.0960, 1.0682) between cobalt-60-based and linac- based treatment plans respectively. Analysis of the treatment indices has shown telecobalt dose conformities and homogeneities to be comparable to those of linac-based despite having higher doses to organ at risk. The end to end test showed a deviation of 1.5% and 0.83% with a tolerance of $\pm 2\%$ between cobalt-60 machine and linac while verification of planned and delivered dose in anthropomorphic phantom showed a deviation of 0.5% and 0% with a tolerance of $\pm 1\%$ between cobalt-60-based plan and

linac-based plan respectively. Hence, both machines were performing according to the calibrated dataset within the tolerance level. Therefore, in situations of inadequate financial capacity and maintenance associated with linear accelerators, the use of telecobalt machines should be encouraged for the benefit of the patients.

DEDICATION

I dedicate this work to my beloved Father and Mother (Mr. Mukone & Mrs. Dyna Kamfosi)

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LIST OF ABBREVIATIONS

3D-CRT	3-Dimension Conformal Radiotherapy
EBRT	External Beam Radiotherapy
ESTRO	European SocieTy for Radiotherapy and Oncology
CC	Collapsed Cone
CI	Conformity Index
CS	Convolution/Superposition
CT	Computed Tomography
DICOM-RT	Digital Imaging and Communication in Medicine-Radiotherapy
DVH	Dose-Volume histogram
D_{max}	Maximum dose
D_{min}	Minimum dose
D_{mean}	Mean dose
HI	Homogeneity Index
IAEA	International Atomic Energy Agency
ICRU	International Commission on Radiation Units and Measurements
IGRT	Image Guided Radiotherapy
IMRT	Intensity- Modulated Radiotherapy
KBTH	Korle-Bu Teaching Hospital
LINAC	Linear Accelerator
MeV	Mega-electron Volts
MLC	Multi-Leaf Collimator
MV	Mega-Voltage
$N_{D,w,Q}$	Calibration factor

NCRNM	National Center for Radiotherapy and Nuclear Medicine
NTCP	Normal Tissue Complication Probability
OAR	Organ at Risk
PTV	Planned Tumor Volume
PET	Positron Emission Topography
PMMA	Polymethylmethacrylate
QA	Quality Assurance
QUANTEC	Quantitative Analysis of Normal Tissue Effect in the Clinic
ROI's	Region of interest
RTOG	Radiation Therapy Oncology Group
RTP	Radiation Treatment Planning
SAD	Source-to-Axis Distance
SGMC	Sweden Ghana Medical Center
SSD	Source-to-Skin Distance
TCP	Tumor Control Probability
TECDOC	Technical Document
TERMA	Total Energy Released in Matter
TPS	Treatment Planning System
TRS	Technical Report Series
UP's	Uninterrupted Power Supply
WHO	World Health Organization

Chapter One

Introduction

1.1 Background

One of the most widely used and effective treatment modalities for the management of cancer is radiotherapy [1]. It may be used for curative or palliative intent to improve the quality of life of a cancer patient. It is estimated that about 52% to 60% of patients would require radiotherapy at least once during the treatment of their ailment and 40% of those patients would be cured of their cancer. Also, 90% of patients requiring radiotherapy for the management of their ailments would be treated with external beam radiation therapy (EBRT) [1, 2]

Radiotherapy involves the use of different types of ionizing radiation (X-rays, gamma rays and more exotic particles such as protons, heavier ions or neutrons) to destroy cancer cells and may be used in combination with other treatment modalities such as: surgery, immunotherapy and/or chemotherapy [2]. Delaney and Barton (2014) identified radiotherapy as specialized treatment for cancer as it offers superior results in survival, local tumor control, quality of symptom relief or side-effect profile when compared to other treatment modalities. They further considered radiotherapy as non-invasive, painless treatment with precise accuracy for tumors [3].

There are two main modes of application of the radiation during radiotherapy: EBRT and brachytherapy. During external beam radiation therapy, ionizing radiation from a source

outside the body is directed at the cancer site while in brachytherapy also called internal radiation therapy or implant therapy, the radiation source is put inside or close to the tumor volume surgically or through an opening found on the body [4].

The most commonly used sources of radiation for external beam radiation therapy are telecobalt machines and linear accelerators. The machines were developed in the early 1950's [2].

Meghzifene, former Head of the Dosimetry and Medical Radiation Physics Section at the IAEA in 2016 report [5], on IAEA 60th General Conference side event said that, "it is important to evaluate each aspect of the equipment choice, first of all, for the anticipated clinical benefits to patients and also the management of the technology over time to ensure that it will deliver consistently safe and effective treatment". He further emphasized that, "If not correctly handled and maintained, radiotherapy equipment may deliver non-optimal treatments to patients and in extreme situations may cause harm".

In support of equipment choice evaluation, Khan (2007) highlighted that the quality of treatment plans and the treatment itself depend on factors such as the equipment at the facility and financial resources to procure and maintain treatment units, imaging equipment, and treatment planning computers [6]. This is also in line with IAEA (2004) technical report series (TRS) 430 which highlights some of the current factors for high quality and effective radiotherapy such as; advancement of treatment planning system, dose algorithms and treatment techniques [7].

Treatment (dosimetric) indices have been introduced in radiotherapy in order to assess the quality of treatment plans. Conformity index (CI) and homogeneity index (HI)

together with other parameters such as maximum dose (D_{max}), minimum dose (D_{min}) and mean dose (D_{mean}) are most commonly used in plan evaluation [8-12].

The analysis tools give a comparison of plans in terms of therapeutic ratio. This is the ratio between the tumor control probability (TCP) and the normal tissue complication probability (NTCP) [6] as shown in Figure 1.1.

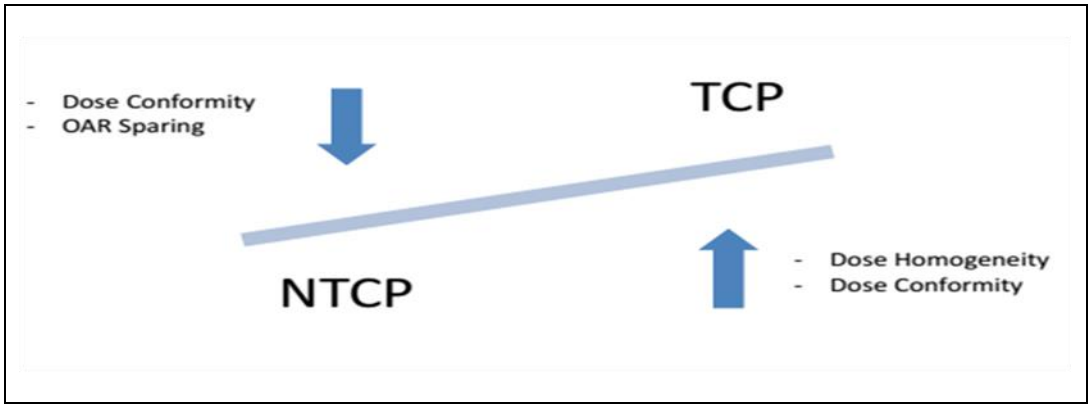


Figure 1.1: Treatment indices used as plan evaluators

Figure 1.1 shows that improved dose homogeneity and dose conformity increases the probability of tumor control while for that of normal tissue complication is reduced with high sparing of organ at risk.

The CI and HI were introduced in radiotherapy by Radiation Therapy Oncology Group (RTOG) in 1993 [12] and have been incorporated in the International Commission on Radiation Units and Measurements (ICRU) report 50 and 62, as part of optimization procedure to achieve the core aim of radiotherapy which is to irradiate the full volume to be treated in a homogeneous way and with minimal dose to the surrounding normal tissues [8, 13].

There are various studies that have used conformity index (CI), homogeneity index (HI) together with maximum dose (D_{max}), minimum dose (D_{min}) and mean dose (D_{mean}) to evaluate different treatment plans. For instance, Petkovska et al. (2010), used conformity index to present the level of conformity achieved by using 3D conformal radiotherapy for brain cancer patients. The results showed that conformity index is a useful quantitative tool for evaluating the quality of a treatment plan [14].

Also Petrova et al. (2017), study on "conformity index and homogeneity index of the postoperative whole breast radiotherapy" observed that a large amount of data contained in the dose-volume histograms and also a large number of curves and lines can complicate the analysis of a radiation plan [9]. Therefore, emerges the need to use a tool that can simplify the analysis of the dose distribution within the target volume and assess the level of dose homogeneity. A study involving 58 patients undergoing postoperative radiotherapy of the whole breast, with their treatment plans assessed using these indices, confirmed that these indices are essential tools during radiation therapy for the analysis of the treatment plans [9].

Furthermore, studies by Feuvret (2006), Helal and Omar (2015), Kartutik et al. (2016), Caraman et al. (2016) [11, 15-17], showed that CI and HI are not only necessary analytical tools for assessing the quality of treatment plans but also "a complementary tool that attributes a score to a treatment plan or that can compare several treatment plans for the same patient" on different machines and treatment techniques.

It is therefore observed that, the choice of treatment units and comparison of conformal radiotherapy plans could be easily facilitated by these treatment indices for effective treatment decision making.

In developing countries deciding how to address the growing and critical need for cancer care remains a challenge. This is mostly experienced when it comes to the choice of treatment machine (telecobalt machine or linear accelerator) to acquire. The choice is always influenced by socio-economic factors. There is therefore the need for one to look at the benefits one is going to get from a particular treatment machine before arriving at a decision [18]. For instance, McClement (2011) reported that, for developing countries within the continent of Africa, patients are treated with the only available treatment machine, mostly telecobalt or linear accelerator (if available) without even evaluating its dosimetric effectiveness to the patient because of inadequate facilities, lack of staff for efficient services, lack of research and training within the region [19].

1.2 Statement of Research Problem

The use of telecobalt machine in radiotherapy is of concern in developing countries where there is a limited resource. In times of economic constraints much more consideration needs to be given to cost and benefit of radiotherapy. This study is undertaken to ascertain if the telecobalt machine could generate and deliver a conformal and homogeneous dose plans more comparable with a highly modern advanced linac machine. This is of significant value when making informed decisions on the choice of radiotherapy machine to use for the best care of patients while taking into consideration economic factors [5, 19-22].

1.3 Objectives

The main objective of this study was to ascertain if it could be feasible to generate and deliver same treatment plans using telecobalt machine with optimal treatment indices, comparable to those of a linear accelerator for some selected common tumor sites.

The specific objectives were to:

1. Compare conformity index (CI), homogeneity index (HI), maximum dose (D_{max}), minimum dose (D_{min}), mean dose (D_{mean}) and doses to organs at risk for breast, prostate and lung cancer cases.
2. Perform plan specific quality assurance on telecobalt and linear accelerator treatment machines.

1.4 Scope and Delimitation

The study was conducted at two radiotherapy centers in Ghana namely; Sweden Ghana Medical Centre (SGMC Cancer Center) and the National Center for Radiotherapy and Nuclear Medicine (NCRNM) of the Korle-Bu Teaching Hospital (KBTH). SGMC and NCRNM use linear accelerator and telecobalt machine respectively for EBRT. The same pre-contoured volumes of the various selected cases were uploaded into the treatment planning system (TPS) in use by the respective radiotherapy center and treatment plans created based on the departmental protocol. The irradiation geometries that gave rise to better target volume coverage and limit doses to delineated normal tissues and organs at risk were opted for based on trial and careful adjustment and selection of beam parameters. Generated treatment plan for particular selected cases were compared to internationally accepted dose constraint protocols (Quantitative Analysis of Normal

Tissue Effects in the Clinics) to access the adequacy of the plan for clinical implementation.

Inter-institutional comparisons of plans were done based on various indices used to evaluate a treatment plan. The treatment plans were subjected to quality assurance by evaluating the deviation between planned dose and delivered dose.

1.5 Thesis Organization

This work is arranged in chronological order of five chapters. Chapter one gives a brief introduction to the research work. Chapter two reviews the existing literature on the research topic. Chapter three focuses on the materials and methodology employed in the study. Results and discussion is presented in chapter four, whereas chapter five presents the conclusion, recommendations and suggestions for further study.

1.6 Ethical clearance

The ethical clearance was waved because the study used retrospective cases from European Society of Radiotherapy and Oncology (ESTRO) solely for research purposes.

Chapter Two

Literature Review

2.1 Introduction

In this chapter relevant literature on the study is reviewed. These include; overview of a telecobalt machine and linear accelerator, treatment planning procedures, dose calculation algorithms, treatment plan evaluation tools and quality assurance of treatment plans.

Favourable treatment outcomes from any radiotherapy treatment technique require that a rightly determined and defined target volume be covered with a uniform dose distribution which should conform to the shape of the target volume as much as reasonably achievable [6]. Radiotherapy treatment outcomes are also dependent on the ability to deliver more than 95% of the prescribed radiation dose to the entire target volume and the use of appropriate fractionation scheme, as well as keeping doses to normal tissues below their tolerances [6]. This suggests that successful evaluation of radiotherapy treatment plans should focus on assessing dose conformity and dose homogeneity to planned tumor volume and dose to organs at risk. Paucity of resources (such as treatment machines and availability of staff with requisite knowledge) influences the radiation dose optimization process, as appropriate irradiation geometries coupled with the right beam energies must be chosen for the treatment of the patient with radiotherapy.

2.2 Overview of telecobalt and linear accelerator

Telecobalt machine and medical linear accelerator are the most commonly used standard treatment machines for modern external beam radiotherapy [2, 3, 5, 7]. The treatment machines have similar configurations with the exception of the method used in generating the useful beam required for treatment and the beam type. A telecobalt machine uses cobalt-60 as radiation source which goes through beta minus decay resulting in the production of two gamma photons having energies of 1.17 MeV and 1.33 MeV respectively, giving the radiation from the cobalt-60 an average beam energy of 1.25 MeV [2, 6].

Medical linear accelerator on the other hand, uses microwave technology to accelerate electrons (produced from an electron gun assembly via thermionic emission) to a very high kinetic energy in a specialized evacuated tube (waveguide), and the accelerated electrons are made to impinge on a tungsten target to produce megavoltage X-rays [2, 4]. It is therefore possible to obtain both photon and electron beams with different energies from the medical linear accelerator. Clinical electron beams are generated by retracting the tungsten target from the path of the pencil electron beam emerging from the waveguide, and then broadening the beam with a scattering foil (the pencil electron beam is made to pass through a thin high-Z metallic foil). For a photon beam, uniformity in fluence across a beam is achieved by passing the X-rays from the target through a flattening filter (metallic cone) to attenuate the X-ray beam more at the central part then at the periphery [2, 6, 24].

Each treatment machine is composed of: a treatment head (or gantry), gantry stand (or support system) and patient support system (or couch). The gantry houses the radiation

source and the collimating systems, and it is mounted isocentrically on the gantry stand making it possible to rotate about the patient. The patient support system is a couch on which the patient lies during treatment delivery. It is configured to move horizontally, laterally and vertically as well as rotating about the horizontal plane, which provides flexibility in the patient setup.

2.2.1 Telecobalt machine

Telecobalt machine commonly called cobalt-60 teletherapy machine was invented in the early 1950s, as the first high energy therapy machine to be applied for external beam radiation therapy modality for the management of cancer. Along the same time the medical linear accelerator was also invented [2].

The past five decades have witnessed a lot of researches and innovation in radiotherapy to the improvement of treatment delivery [3, 19, 20, 23, 25]. Feain et al. (2016), Healy et al, (2016) list some of the emerging innovations such as: implementation of three dimensional conformal radiation therapy (3D-CRT), intensity-modulated radiation therapy (IMRT), image guided radiation therapy (IGRT), stereotactic radiosurgery (SRS), stereotactic body radiotherapy (SBRT), and robotic radiotherapy [23, 25].

The researches have lead to lot of design innovations being introduced into the medical linear accelerator, but since the invention of the cobalt-60 teletherapy machine there has been very little change in ancillaries and accessories on the machine. Studies have shown that most of the stipulated advanced treatment modalities have been implemented with linear accelerators [23]. Notwithstanding the above, studies are on-going to equip cobalt-60 machine with multi-leaf collimators (MLCs), which are important elements for effective delivery of conventional 3D-CRT and a basic requirement for IMRT technique

implementation [4, 20, 24]. Currently, there are commercially available cobalt-60 teletherapy machine fitted with MLCs, which are solely used for field shaping purposes. Figure 2.1, shows a Co-60 machine used for external beam radiotherapy.

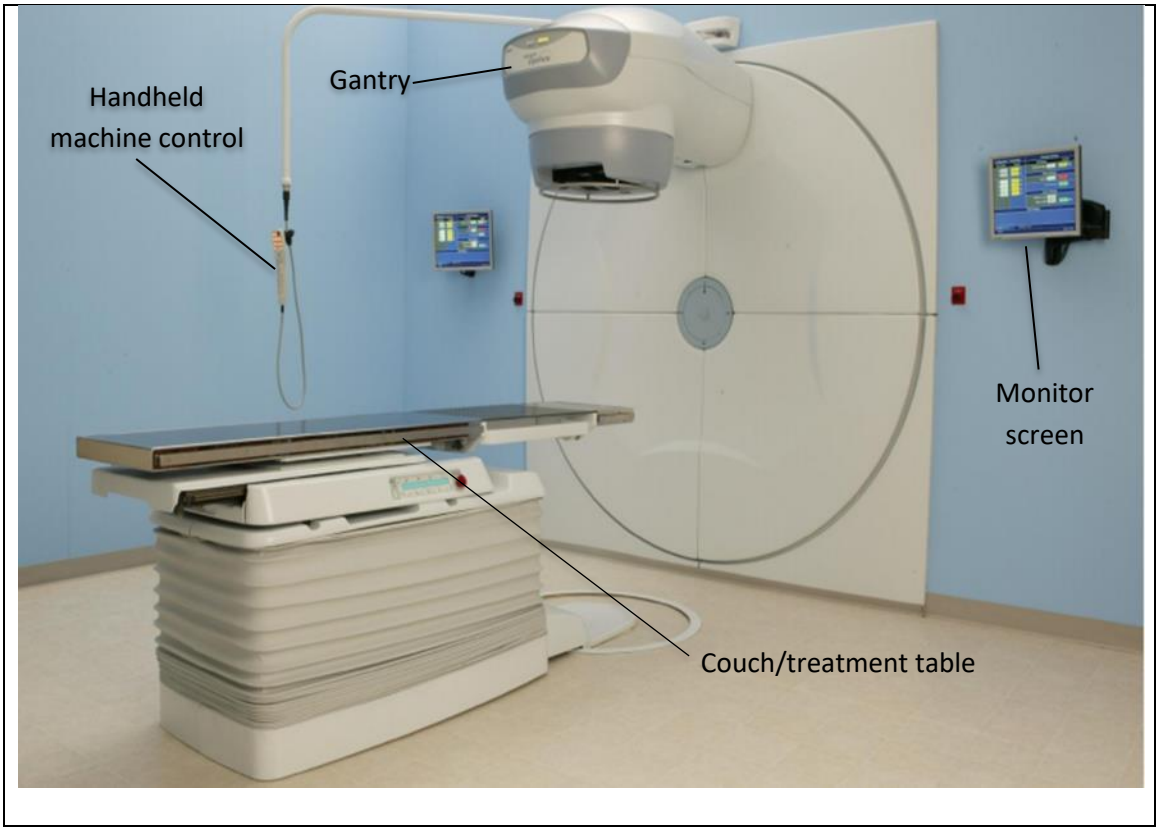


Figure 2.1: Cobalt-60 Teletherapy machine
(Source: Radiation Oncology Physics: A Handbook for Teachers and Students pp.154, [2])

2.2.2 Linear Accelerator (Linac)

The medical linear accelerator is a modern machine that is being used in radiotherapy for treatment of cancer. The machine has undergone improvements in technology, design, ancillaries and utility. It has the ability to treat cancer of almost all body sites, owing to enhanced features incorporated into the machine to give it the capacity to be used for advanced treatment techniques such as: IMRT, IGRT, SRS and SBRT.

Multi-leaf collimators (MLCs) are currently basic features of modern linear accelerators. MLCs are tertiary collimator system attached to the main collimator system of a linac, and consist of independently computer driven leaves with very small widths found within two opposing banks, which are used to define the shape of a beam and can also be used to modulate fluence distribution across a beam [2, 4]. This has helped to improve accuracy in executing treatment. A typical example of linear accelerator is shown in Figure 2.2.

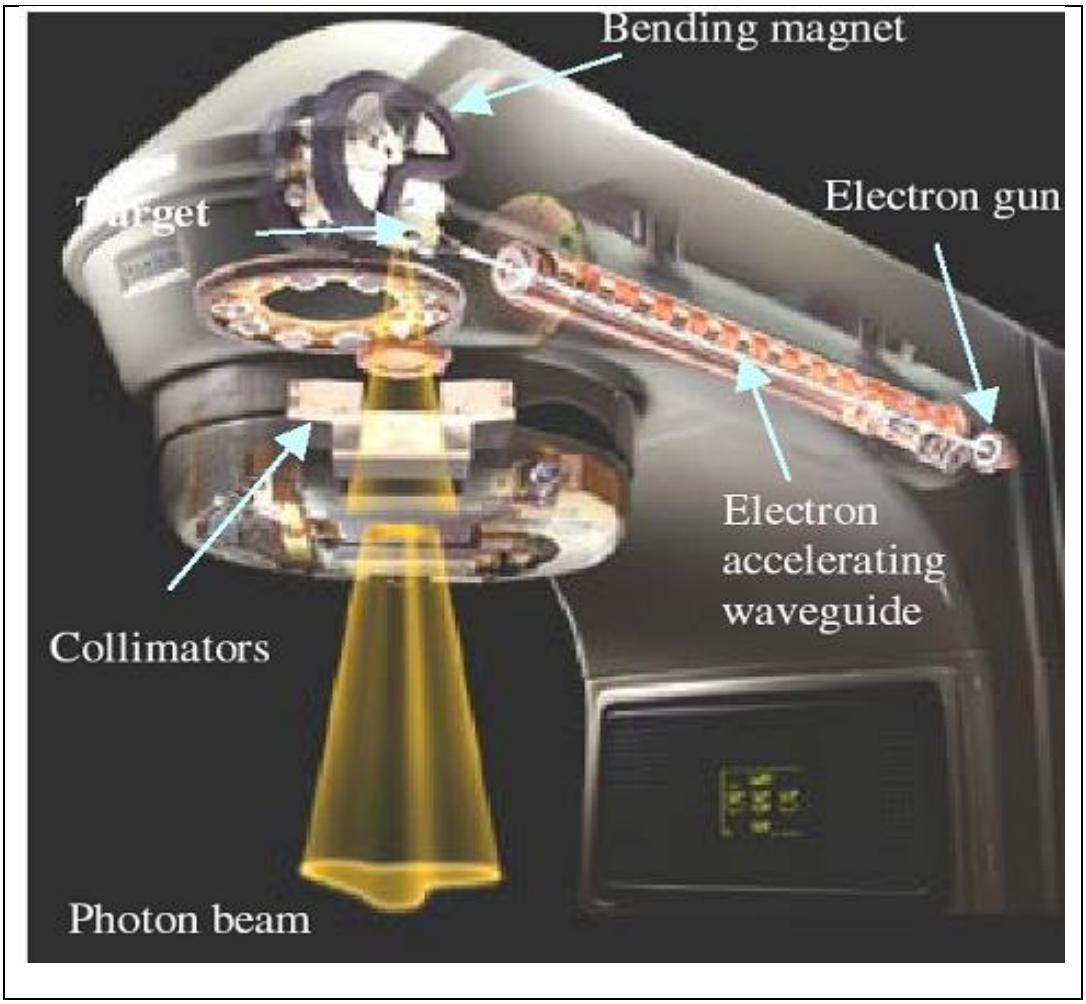


Figure 2.2: Typical modern dual energy linac
(Source: Lecture notes on "Medical Linear Accelerators in Radiation Therapy. Haijun Song, Ph.D. Dept of Radiation Oncology, Duke University Medical Center". Retrieved on 25/09/2017)

2.2.3 Comparison of cobalt-60 teletherapy machine and linear accelerator

There are various advantages and disadvantages between cobalt-60 teletherapy machine and linear accelerator. Mostly, comparisons are made on safety (shielding requirements), dosimetry, treatment duration (time), patient clinical benefits, cost and maintenance, staffing, security and infrastructure [2, 20, 25].

a) Safety

On safety aspect, cobalt-60 radioactive source in cobalt-60 teletherapy machine can be very hazardous in the event of leakage or misplacement of the source. Also whether the machine is beam-OFF or Beam ON position, some leakage radiation will escape from the telecobalt machine [2]. In the case of linear accelerators, there are no radioactive isotopes; with the X-rays generated the radiation beam is "ON" position only when the machine is 'ON'. For this reason, personnel safety in the treatment room should be maintained.

b) Dosimetry

Cobalt-60 teletherapy machine uses radioactive isotope, and there is therefore the need to have the source replaced every 5 to 10 years due to the decay of the source. Consequently, physicists have increased pressure to continually calculate new treatment times or update previously calculated treatment times as the source decays [4].

Further to that, cobalt-60 teletherapy machine produce average energy 1.25 MeV gamma rays while a linear accelerator can generate megavoltage X-rays beams having energies ranging from 6 - 25 MeV and a number of clinical electron beams with energies ranging from 6 - 30 MeV. Also beams from linear accelerator are characterized with small beam penumbra, modulated dose rate and smaller focal spot size. These attributes provide linear accelerator with a high probability of creating an optimal treatment plan for conformal dose distribution while sparing normal tissues [6, 25-26].

c) Treatment duration (Time)

WHO reports that cancer rate and demand of cancer patients for radiotherapy is increasing tremendously [1]. Approximately, 40-50 patients, with about 10-15 minutes

each can be treated on cobalt-60 teletherapy machine daily. However, for linac machine the treatment time can be significantly reduced to less than 5 minutes, thus decreasing the time spent by patients within the treatment bunker (or room) [2].

d) Patient Clinical benefits

Clinically, linac high energy X-ray beams has more penetration as compared to cobalt-60 beams. Thus treatment of deep seated tumors like prostate, cervical and others can be done with assurance and also with much sparing of organs at risks. Study by Healy et al. indicated that complex treatment techniques are achieved by linac because of being sophisticated and the availability of high-energy beams which are useful for certain treatments [25].

Healy et al. (2016) claim supports Mayles et al. (2007) who had compared modern linear accelerators with cobalt-60 units, and observed that a larger penumbra and greater mechanical inaccuracy give poorer geometrical precision for treatment with cobalt-60 teletherapy machines [25, 26].

Mayles et al. (2007) hold a strong view that, cobalt-60 units may be quite suitable mostly for non-radical cancer treatment (medical treatment unintended to remove the source of a disease, rather simply treat the symptoms) [26].

e) Cost and maintenance

Cobalt-60 teletherapy machine stand a better chance than linac when it comes to the issue of cost and maintenance. Studies have established that cobalt-60 teletherapy machine has: a significantly lower capital and installation cost, lesser demand for servicing and maintenance, lesser dependence on reliable electrical power, simple in design and easy

to operate [2, 19, 22]. On the other hand, Healy et al. (2016) associated the high cost and maintenance for linear accelerators to the complex electric components used in the linear accelerators [25].

However, McClement (2011) in his assessments on whether Africans are capable of using linear accelerators in radiotherapy, maintain a strong view that indeed developing countries in the continent of Africa are not only capable of handling, using and maintaining a linear accelerator but also deserve advanced and sophisticated mode of radiotherapy treatment [19]. The assessment draws attention to some of the following observed facts on linac:

Firstly, almost all developed countries are relying on linear accelerators as their best treatment machines in radiotherapy. This has attributed to better cancer management for those countries as clearly reflected by low statistical cancer mortality rate according to WHO 2012 data which shows that approximately 70% of deaths from cancer occur in low-and middle-income countries [1].

Secondly, it is easy to operate a linear accelerator because of built in automated processes and safety mechanisms which are standard features that offer consistent working process for better-quality and safety.

Thirdly, cobalt-60 teletherapy machine started being replaced by linac 35 years ago, therefore, in 10 years' time Africa will be 45 years behind the rest of the radiation oncology world which will result in a continued poor health care of cancer patient

Lastly, the five-year survival rate in percentage from 1960 to 2000 (in 1960 it was 37.5%, in 1970 it was 44.6%, in 1980 it was 49.5%, in 1990 it was 53.5% and in 2000 it

was 56.5%) is definitely more pronounced since the introduction of linear accelerators, and of course is steadily increasing due to new developments in cancer treatment. In support of this, Baert et al. (2006) observed tremendous improvements among breast cancer patients care due to breast cancer screenings programmes, treatment machine and advanced technologies [27].

On the major issue of electricity problem in African countries, McClement (2011) recommended that, this can easily be overcome with generators and uninterrupted power supply (UPS's), which are in itself developing each day to stand the test of time [19].

Further comparision of cobalt-60 teletherapy machine and linear accelerator for dosimetric parameters is shown in Table 2.1 obtained from Ravichandran (2009) study [22].

Table 2.1: Comparison of teleobalt and linear accelerator machines
(*Source: Adapted from a study done by R. Ravichandran [22] at Patel Hospital*)

FEATURE	Cobalt-60	Linear accelerator
ENERGY	Inferior in matter of deep seated tumor	Higher energies hence able to treat deep seated tumors.
DOSE RATE	Reduces with time due to radioactive decay	Does not change
PRECISION	Less precise	More precise because the doses are continuously monitored and recorded
MINIMUM FIELD SIZE	5 x 5cm^2	0.5 x 0.5 cm^2, hence able to treat very small areas/field
		Generate electron beams as

ELECTRON BEAM	Not possible	such superficial tumors are treated easily.
STEREOTACTIC RADIOTHERAPY	Not possible	Possible
DISPOSING SOURCE	Major environmental problem	No source disposal as such better safety.
SOURCE CHANGE	Every 5-10 years	None
RADIATION LEAKAGE	Some radiation is always in the room and never zero	No radiation in the room once the machine is "off" position
PENUMBRA	90 – 10% is 1.5cm field definition	80% sharp beam field definition
SKIN DOSE	15 – 25%	40 – 50%
BEAM COLLIMATION	MLC being tried	MLC, Asymmetric collimators
IRREGULAR FIELDS	Achievable with blocks	MLC
SHAPE OF ISODOSE CURVES	Rounded beyond central zone	Flattened with special filter
BUILD-UP	5mm	28 - 35mm

2.3 Future of cobalt-60 teletherapy machine in radiotherapy

Abdel-Wahab et al., in their report on the status of radiotherapy resources in Africa indicates a great decrease in cobalt-60 teletherapy machine. The report showed that 60% of radiotherapy machines in Africa were cobalt-60 units in 1998 compared with 32% in

2013. Hence in 2013, of the megavoltage machines, 32% (88) were cobalt-60 machines, and 68% (189) were linear accelerators [40].

On the other hand, Zubizarreta et al. (2015) reported that telecobalt machines represent only 7% of the external beam radiotherapy equipment in high income countries (HIC) and 30% in Africa [41]. In general, as improved techniques and modalities became available, cobalt-60 machines have over time been retired and replaced with more up-to-date equipment and are now almost extinct in the United States observed Ravichandran (2009) [22].

Healy et al. (2016), further highlight that the IAEA/WHO TLD audit programme of 2016 has shown decreasing demand by hospitals for cobalt-60 audit over linac machine. The most recent data show more than 80% of requests are for audits of linacs, a clear indication of an increasing number of linear accelerators in radiotherapy departments [25]. All these reports really draw our attention to the current reliance on linear accelerators for quality health care of patients in radiation oncology.

2.4 Radiotherapy Treatment Planning Procedures

Recommended radiotherapy procedures are issued by the International Commission on Radiological Units and Measurements (ICRU) to ensure that all procedures can be achieved repeatedly and qualitatively [7, 8, 13].

The process involves first, determining the location, the extent, the stage and the shape of the tumor. Having this clinical information, the clinician may decide to use external beam therapy with a treatment prescription being issued. Then additional data are required from computed tomography (CT), magnetic resonance imaging (MRI) scans or other imaging

modalities such as PET-CT, Ultrasound, SPECT for the planning stage of the treatment [6, 28, 29].

Making use of such diagnostic information, regions of interest (ROIs) in terms of volumes, which influence the planning process, are delineated to describe the patient contours, the position and shapes of the organs are defined according to ICRU recommendations [8,13].

Depending on the geometry of the ROIs and the clinical specifications, beam arrangements are selected by the treatment planner (medical physicist/dosimetrist) to optimize radiation dose to the intended target volume with the aid of a treatment planning system (TPS). The TPS calculates and displays dose distributions, as well as provide duration of treatment to achieve the desired dose distributions. In most cases the planner manipulates the irradiation geometries (beam angulations, beam collimations, beam weighting, adding beam modifiers) by trial and error bases, and then selects an optimal treatment plan (or irradiation geometry). Each treatment plan proposed by the treatment planner is verified by the clinician. The treatment is then delivered with the radiation therapy machine set in accordance with the plan specifications [6, 8, 13, 28, 29].

2.4.1 Treatment planning system (TPS)

Computerized treatment planning system (TPS) comprises mainly of a hardware system and a software system which has patient data, machine data and dose calculation algorithms [2, 4]. The main purposes of TPS in EBRT are to assist with the realization of the dose distributions within the irradiated region of a patient prior to treatment delivery and also serve as dose optimization tool [6, 31].

This TPS in radiation therapy allows dosimetrists, physicists, and physicians to generate, choose and verify the treatment plans with high quality helping to achieve the intended purpose for the benefit of the patient [28, 32].

2.4.2 Levels of dose planning and treatment

There are three levels of dose planning and treatment delivery in EBRT described by Barrett et al. (2009) [32]. These levels are conventional, conformal and complex treatment. The conventional (2D) treatment uses single or opposing beams, with or without 2D dose distributions, with simple shielding and compensators while three dimensional conformal treatments (3D-CRT) involves delineation of the target organ and surrounding critical organs according to ICRU principles with 3D dose calculations using blocks/MLCs to shape beams. The third one, complex treatment is where advanced treatment techniques such as; IMRT, dynamic treatments, IGRT and 3D or 4D deliveries are used to shape the fluence of the beam so that it conform to the target volume [6].

However, currently due to lack of MLC's in cobalt-60 teletherapy machines, the complex treatment techniques are only carried out by linear accelerators [4, 6, 28, 32].

2.5 Dose and volume specification

The International Commission on Radiation Units and Measurements (ICRU) has come up with a systematic approach to the whole processes of dose and volume definitions for prescribing, recording and reporting photon beam therapy [8, 13]. The dose and volume definitions are essential for meaningful 3D treatment planning and for accurate dose reporting as well as comparison of treatment plans on the center or from different centers.

Both ICRU Reports 50 and 62 recommend dose uniformity in the target volume to be within +7% and –5% of the dose delivered to a well-defined prescription point (ICRU reference point) within the target [8, 13]. This means that at the ICRU reference point a prescribed dose is 100% and then the maximum and minimum doses recommended within the planned target volume are 107% and 95% respectively.

2.5.1 Volume definitions

The following volumes have been defined in the ICRU Reports 50 and 62 as principal volumes related to 3D treatment planning [8, 13, 7, 31].

a) Gross tumor volume (GTV)

The Gross Tumor Volume is the gross palpable or visible/demonstrable extent and location of malignant growth.

b) Clinical Target Volume (CTV)

The clinical target volume is the tissue volume that contains a demonstrable GTV and/or sub-clinical microscopic malignant disease, which has to be eliminated. This volume thus has to be treated adequately in order to achieve the aim of therapy, cure or palliation.

c) Internal Target Volume (ITV)

The ITV consists of the CTV plus an internal margin. The internal margin is designed to take into account the variations in the size and position of the CTV relative to the patient's reference frame (usually defined by the bony anatomy).

d) Planning Target Volume (PTV)

The planning target volume is a geometrical concept, and it is defined to select appropriate beam arrangements, taking into consideration the net effect of all possible

geometrical variations, in order to ensure that the prescribed dose is actually absorbed in the CTV.

Included in the PTV are the internal target margin and an additional margin for set-up uncertainties, machine tolerances and intra-treatment variations.

e) Organ at Risk (OAR)

The organ at risk is an organ whose sensitivity to radiation is such that the dose received from a treatment plan may be significant compared with its tolerance, possibly requiring a change in the beam arrangement or a change in the dose.

2.6 Treatment Planning Algorithms

The dose algorithm software is the most unique, critical and complex piece of the TPS software [6]. It is responsible for the correct representation of dose in the patient and most results of dose calculations are frequently linked to beam-time or monitor units (MU's) calculations. Therefore, many clinical decisions are taken on the basis of the calculated dose distributions [4, 31].

There are two types of algorithms for photon beam; model based algorithms and correction-based algorithms [4]. Model-based algorithms directly compute the dose to the patient by modeling the beam and its interactions in the patient representation where changes in lateral electron and photon transport are not modeled (no lateral transport). Minimal amount of beam data measured in a water phantom are therefore required to fine tune the algorithm.

On the other hand, correction-based algorithms use beam data measured in water phantoms and apply corrections to the data to obtain what would be pertaining in a patient [6, 26, 28]. Correction-based algorithms rely heavily on measured beam data. There is therefore no clear distinction between both algorithms as all require beam data to function effectively.

Haas (1999) established that the current generation of treatment machines uses model-based dose algorithms which deliver optimized or intensity-modulated radiotherapy as well as other advanced treatment techniques [28].

The convolutional/superposition (CS), collapsed cone (CC) and the Monte Carlo are some examples of a model-based dose calculation algorithm but it is convolution/superposition and collapsed cone algorithms which are most commonly used in today's commercial treatment planning systems. Khan attributed the reason to fast and advanced computers which are able to calculate complicated algorithms in a reasonable time. Moreover, Khan (2007) revealed that radiotherapy treatment planning (RTP) has entered the model-building phase of computations hence most current TPS and linear accelerators are built with model based algorithms [6].

In the case of clinical electron beams from linear accelerators, pencil beam algorithm based on Gaussian pencil beam distributions (multiple scattering theory) is employed. Pencil beam algorithm allows for calculation of dose distribution for fields of any shape and size, irregular or sloping surface contours, and tissue heterogeneities in three dimensions. The most observed limitation is inaccuracies of dose distribution at

interfaces of different density tissues such as tissue-lung, tissue-bone, and bone edges [6, 26, 28].

Understanding the performance of algorithms used in a TPS would not only aid the user to determine the proficiencies and limitations of the algorithms but also would help the user to diagnose TPS problems and developing QA processes. This is so because each dose calculation algorithm has its own characteristics and options [6].

2.7 Treatment plan evaluation

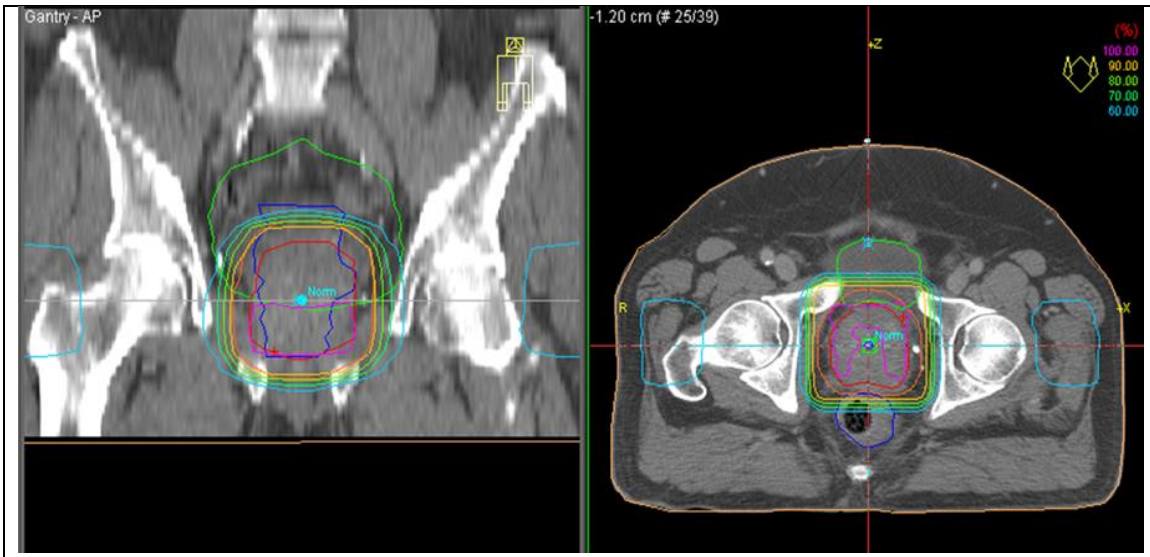
There are two general sets of tools for plan evaluation, one based upon physical endpoints and the other based on biological endpoints [4, 32]. To attain quantitative biological endpoints, models involving biological indices have been developed. Examples of such models are; tumor control probability (TCP) and normal tissue complication probability (NTCP). However, Khan [4] observed that currently most evaluations are carried out on the basis of physical endpoints because clinical data required to validate treatment plans based on biological models are scarce.

The physical endpoints involves evaluation of dose and dose–volume parameters including such quantities as dose to a point in the volume of interest, maximum dose (D_{max}), minimum dose (D_{min}), mean dose (D_{mean}) or the volume of the structure receiving a specified dose or higher. These quantitative and qualitative parameters provide relatively simpler means of ensuring that the treatment has been delivered in such ways as to achieve favourable treatment outcomes [33, 34].

The following physical tools are commonly used to evaluate the dose distribution in a plan; Isodose lines, dose statistics and Dose-Volume Histogram (DVH) [32].

2.7.1 Isodose lines/curves

Isodose lines are lines passing through points of equal dose drawn at regular intervals of absorbed dose and expressed as a percentage of the dose at a reference point [2]. They assess treatment plans along a single plane or over several planes in the patient. If the isodose values are within a desired range, according to ICRU 50 or 62 that is minimum isodose 95% and maximum isodose 107% of the prescribed dose to reference point, the plan may be accepted provided the doses to organ at risks are within their respective tolerances [8, 13]. An example of spatial distribution of isodose lines superimposed on patient anatomy generated with a TPS is shown in Figure 2.3.



a. coronal view b. axial view

Figure 2.3: Isodose lines to treat carcinoma of the prostate
(The colors correspond to percentage of dose at reference point: blue-60%, green- 70%, light green- 80%, yellow- 90%, violet- 100%)

2.7.2 Dose statistics

In calculating the dose distribution within a patient, the TPS segment the patient into very tiny voxels and the dose computation is done on voxel-by-voxel bases. With reference to this, there is the possibility of obtaining statistical representation of the dose distribution.

In contrast to isodose lines, dose statistics provide quantitative information on the volume of the target or critical structure and on the dose received by that volume [4]. Fundamental statistical data are calculated from the matrix of doses to each volume element within an organ. These include; the minimum dose to the volume, the maximum dose to the volume, the mean dose to the volume, the dose received by at least 95% of the volume, the volume irradiated to at least 95% of the prescribed dose contrast to isodose lines, dose statistics provide quantitative information on the volume of the target or critical structure and on the dose received by that volume [31].

2.7.3 Dose–Volume Histograms (DVH)

Dose-volume histograms on the other hand summarize the data contained in the 3D dose distribution. DVH is extremely powerful tool for quantitative evaluation of treatment plans [2]. Khan (2014) and other authors have recommended DVH as the basic tool for plan evaluation and this is why DVHs are now a routine planning evaluation tool [4, 20, 26, 31, 34].

In general, the DVH represents a frequency distribution of dose values within a defined volume that may be the PTV itself or a specific organ in the vicinity of the PTV [4]. However, rather than displaying the frequency, DVHs are usually displayed in the form of 'per cent volume of total volume' on the ordinate against the dose on the abscissa [2] as shown in Figure 2.4.

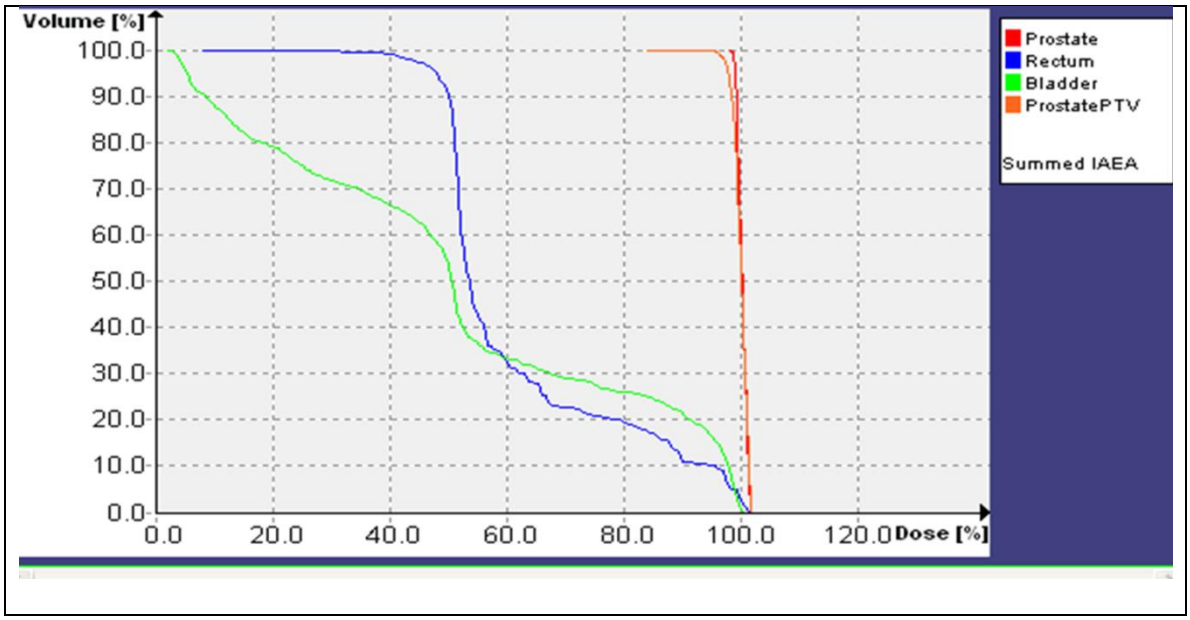


Figure 2.4: DVH of the prostate case showing dose versus volume

Despite that DVH is a great tool for plan evaluations or comparing competing plans, Myles (2007) questioned its applicability to plans which have been computed with different dose computational parameters or using different algorithms because there are always some uncertainties related to DVH calculation and representation [26]. This is because different dose calculation algorithms may not handle heterogeneities, or the penumbra. As such it is recommended that DVHs must be used together with other treatment evaluation parameters.

2.8 Treatment Indices

The conformity index (CI) and the homogeneity index (HI) are two most commonly used analysis tools for conformal radiotherapy treatment plans [16]. The other indices include energy index (EI), selectivity index (SI), integral dose (ID) and gradient index (GI) [14, 15, 36, 21]. All the listed indices are purely physical quantities based on dose-volume constraints.

Various studies have established that in conformal radiotherapy due to the huge amount of data, along with ever more advanced and sophisticated systems, these indices simplify treatment decisions by providing unique quantitative information regarding the quality of a treatment option. As such they are used to assess the quality of treatment plans [11, 15, 21, 38].

In a related study conducted by Adams and Warrington (2008) who compared plans between cobalt and linear accelerator-based treatment plans for conformal and intensity-modulated radiotherapy, they used: DVH, minimum dose (%), maximum dose (%), mean dose (%), $V_{95\%}$ (%) of the PTV as well as dose volume constraints for critical organs rather than indices to evaluate and compare the plans. The study was conducted with six patients, for different treatment sites (breast, oesophagus, meningioma, parotid, prostate and thyroid). In the planning both X-ray photons (6/10 MeV) and cobalt-60 gamma rays (average 1.25 MeV) were used. Their findings indicated that, in all cases, the cobalt-60 plans were comparable to those created using medical linear accelerator with 6/10 MeV photons and MLC. In most cases, this was achieved with the same beam arrangement although in some cases, such as the prostate, additional fields were required [20].

Adams and Warrington (2008) hold a strong view that, it is possible to design high-quality radical radiotherapy treatments using cobal-60 teletherapy units [20]. However, the study also made acknowledgement that for cobalt-60 to be able to offer such comparable and efficient alternative to MLC-based linac treatments techniques; it would require a well-designed beam blocking/compensation system and the ability to perform electronic verification imaging.

As suggested by Feuvret et al. (2006), further study was needed to verify the dose conformity and dose homogeneity using indices rather than DVH and isodose lines alone [11].

Literature has shown that there are a number of studies that have used conformity index and homogeneity index to compare different plans on linac only for selected cases, selected treatment techniques and selected beam energy or number of beams/fields [9-11, 14-18, 21].

However, little research has been done on these indices to compare between telecobalt and linear accelerator-based treatment plans for selected conformal radiotherapy. Hence this study was designed to compare the two treatment machines based on CI and HI.

2.8.1 Conformity Index (CI)

The RTOG (1993) define conformity index (CI) as the ratio of volume receiving reference isodose ($\boldsymbol{V_{RI}}$) and the planned target volume (***PTV***), see Equation 2.1 [8, 11, 12].

$$\boldsymbol{CI_{RTOG}} = \frac{\boldsymbol{V_{RI}}}{\boldsymbol{PTV}} \qquad (\mathbf{2.1})$$

where ($\boldsymbol{V_{RI}}$) is the ratio of volume of the total tissue receiving at least 95% ($V_{95\%}$) of prescribed dose to PTV according to ICRU 62 [8].

A conformity index of 1 indicates that 100% of a prescription dose is delivered to the PTV, and no dose is delivered to any adjacent tissue. For most clinical cases, the CI is less than 1. A higher CI value indicates that the irradiated volume is greater than the target volume and includes healthy tissues. Likewise, if the conformity index is less than 1, means that the target volume is partially irradiated [11].

The index values obtained from above equation 2.1 are interpreted based on Table 2.2 summary as per RTOG protocols [9, 12].

Table 2.2: CI-Value and RTOG interpretation

CI-Value	Meaning
<1	Target partially irradiated
1	Ideal conformation
>1	Irradiated volume greater than planned volume
Range (2-2.5 and 0.9-1)	Minor violation of the protocol
<0.9 and >2.5	Major violation of the protocol

2.8.2 Homogeneity Index (HI)

Shaw (1993) defined homogeneity index as a ratio of the maximum dose ($\boldsymbol{D_{Max}}$) in the target volume to the prescribed dose ($\boldsymbol{D_p}$), see equation 2.2 [12].

$$\boldsymbol{HI_{RTOG}} = \frac{\boldsymbol{D_{Max}}}{\boldsymbol{D_P}} \qquad (\mathbf{2.2})$$

A homogeneity index shows the intensity of dose distributions in target region. Hence those plans with both “hot spot” and “cold spot” could be distinguished by this index [37].

In literature certain other definitions and formulae of HI were later derived, however none has been described as ideal or near ideal for calculating HI [15, 38].

However, due to paucity of data regarding the ideal HI formula, Kataria et al. (2012) reviewed five definitions/formulae of HI including equation 2.2 above [38]. The results showed that the RTOG formula given in equation 2.2 correlates positively with equation

2.3 below even though there was a considerable agreement between HI calculated by other formulae.

$$\boldsymbol{HI} = \frac{\boldsymbol{D_{\geq 5\%}}}{\boldsymbol{D_{\geq 95\%}}} \qquad (\mathbf{2.3})$$

Where $D_{\geq 5\%}$ = minimum dose in 5% of the Planning Target Volume (PTV), indicating the "maximum dose", and $D_{\geq 95\%}$ = minimum dose in 95% of the PTV, indicating the "minimum dose". The lower the index value obtained, the better the dose homogeneity [12, 15, 37]. Table 2.3 gives the summary of HI-values and its interpretation.

Table 2.3: HI-Value and RTOG interpretation

HI-Value	Meaning
<1	Less homogeneous
1	Homogeneous treatment plan
≤2	Comply with the protocol
Range (2-2.5)	Minor violation of the protocol
>2.5	Major violation of the protocol

Kataria et al. (2012), as well as Helal and Omar (2015) both have established that HI basically is the ratio between the maximum and minimum dose in the target volume [38, 15]. The HI of 1 represents the ideal uniform dose within a target while higher HI values indicate greater dose heterogeneity in the PTV.

Despite aiding in conformal radiotherapy planning evaluation, some studies have shown less emphasis on CI and HI indices arguing that there are several open questions concerning the weight of their interpretation and the limited information about a possible correlation between clinical data and theoretical parameters. However, those who have used these indices acknowledged that they are good indicators for pattern of dose distribution in a target volume [9, 15, 22,].

2.9 Quality Assurance (QA) in Radiotherapy

The quality assurance/control activities such as end-to-end test, machine output and in-vivo dosimetry (IVD) are conducted in radiotherapy not only to assess the quality of the whole treatment process for dose calculations and distributions but also to detect majors errors, evaluate the clinically relevant differences between planned and delivered dose [34, 42]

IAEA (2008) TECDOC 1583 recommends that, QA in the radiation therapy treatment planning process is essential to ensure accurate dose delivery to the patient and minimizes the possibility of accidental exposure [39].

Through QA programs it is ensured that each step has as low uncertainties as possible. On the other hand, Mayles et al. (2007) noted that innovative advancements in the technology of detectors, dose-calculation algorithms and the stability of linear accelerators have reduced the level of uncertainties [26].

Chapter Three

MATERIALS AND METHODS

3.1 Introduction

This chapter outlines in detail the materials and planning methods employed in this study. The study was conducted at two radiotherapy centers in Ghana; Sweden Ghana Medical Centre (SGMC Cancer Center) and National Center for Radiotherapy and Nuclear Medicine (NCRNM), Korle-Bu Teaching Hospital (KBTH). SGMC and NCRNM use linear accelerator and telecobalt machine respectively for EBRT. The recommended planning protocols set in literature on how to prescribe, record and report photon beam therapy were followed until the plan was ready and approved for treatment. Treatment plans for breast, prostate and lungs were accomplished by qualified medical physicists and clinically approved for treatment. The treatment plans were subjected to quality control.

3.2 MATERIALS

The following materials were employed in the study:

- Retrospective CT scans of patients with breast, prostate and lung cases
- Elekta Synergy platform linear accelerator teletherapy unit
- Theratron Equinox 100 cobalt-60 teletherapy unit
- Oncentra masterplan 3D treatment planning system (version 4.3)
- Prowess Panther 3D planning system (version 4.6)
- Siemens computed tomography unit
- Farmer type ionization chamber
- PTW Unidos electrometer
- Druck pace 1000 Barometer

- Testo 925 digital thermometer
- PMMA and anthropomorphic phantoms
- GAFchromic films
- Diodes with reader

3.2.1 Retrospective CT scans of Patients

The retrospective CT scans of patients earmarked to be treated for breast, prostate and lung cancers were used in this study. The CT data sets were obtained from the European Society for Radiotherapy and Oncology (ESTRO), which were meant to be used for an institutional inter-comparison treatment planning contest. ESTRO is non-profitable and scientific organization that promotes innovation, research and dissemination of science in radiation oncology to improve patients care in its multimodality treatment of cancer [43]. Normal tissue and target segmentation processes had already been carried out for the CT data sets to ensure reproducibility of delineated volumes, and the images saved in DICOM-RT format.

3.2.2 The Linear Accelerator

At SGMC Cancer center, the linear accelerator is an Elekta Synergy Platform (Elekta Limited, Crawley, UK, serial No: 1175, Year: 2012) shown in Figure 3.3. The machine has capabilities for delivering high photon energy and electron energy beams (6 MeV and 15 MeV photon energies and 6 MeV, 10 MeV and 15 MeV energies for electron). The machine also has a multi-leaf collimator that shapes the radiation fields to tumor site. The machine is equipped with an on-board imager (EPID); an imaging tool that ensures radiation will be delivered accurately during all treatment sessions. This linear accelerator has capabilities for delivering the following treatment modalities: Three dimensional conformal radiotherapy (3D-CRT), Intensity modulated radiotherapy (IMRT),

volumetric-modulated arc therapy (VMAT), and stereotactic radiosurgery (SRS) but currently have license to plan 3D-CRT technique.

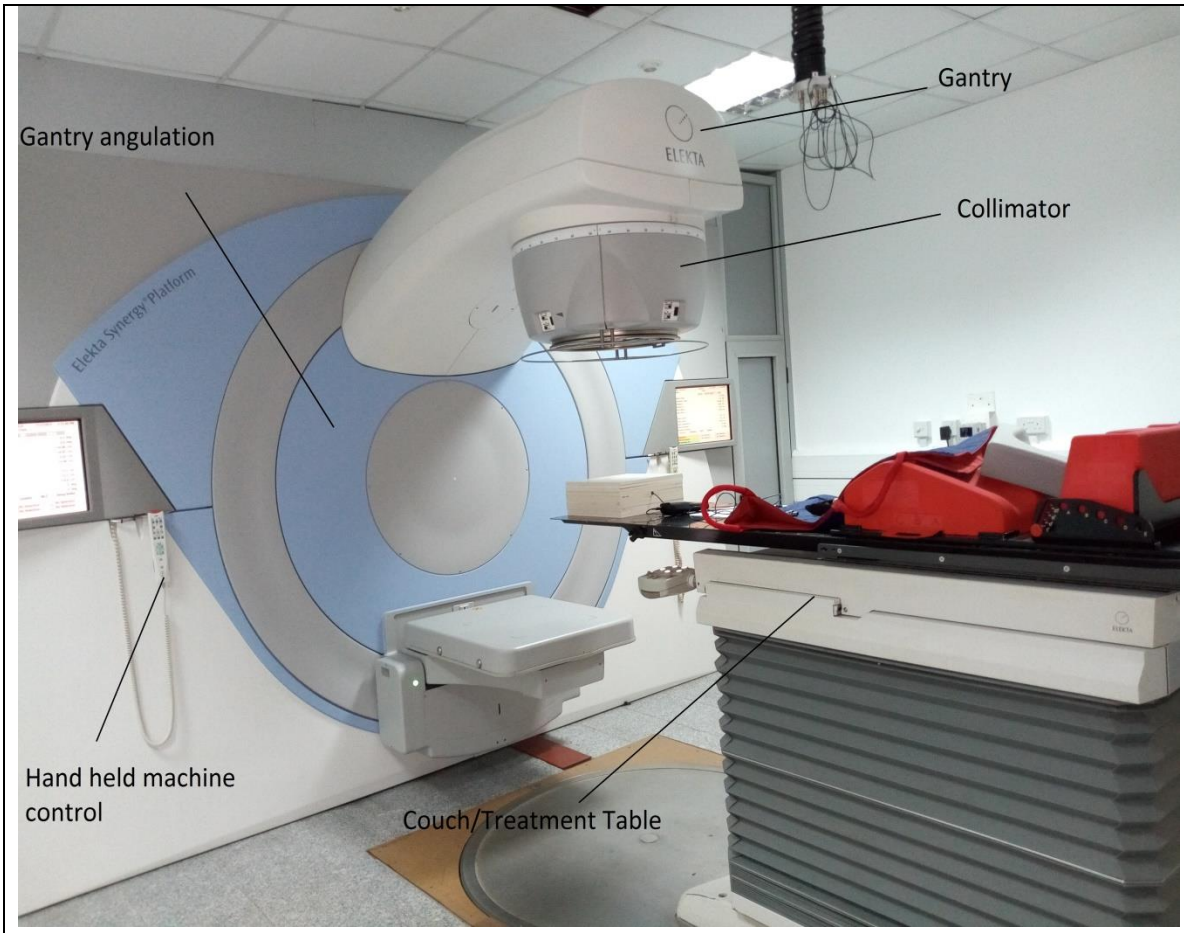


Figure 3.1: Elekta linear accelerator

3.2.3 Theratron Equinox 100 cobalt-60 unit

Figure 3.2 shows Theratron Equinox 100 cobalt-60 unit (Best Theratronics Limited, Canada, S/N: 2117), used at NCRNM for external beam radiotherapy. The machine is a fully computerized isocentric teletherapy system with software that keeps the vital operational history of the unit. Additionally, it has a motorized and physical wedge,

AVANZA treatment position table with carbon fiber top, as well as collision detector system.

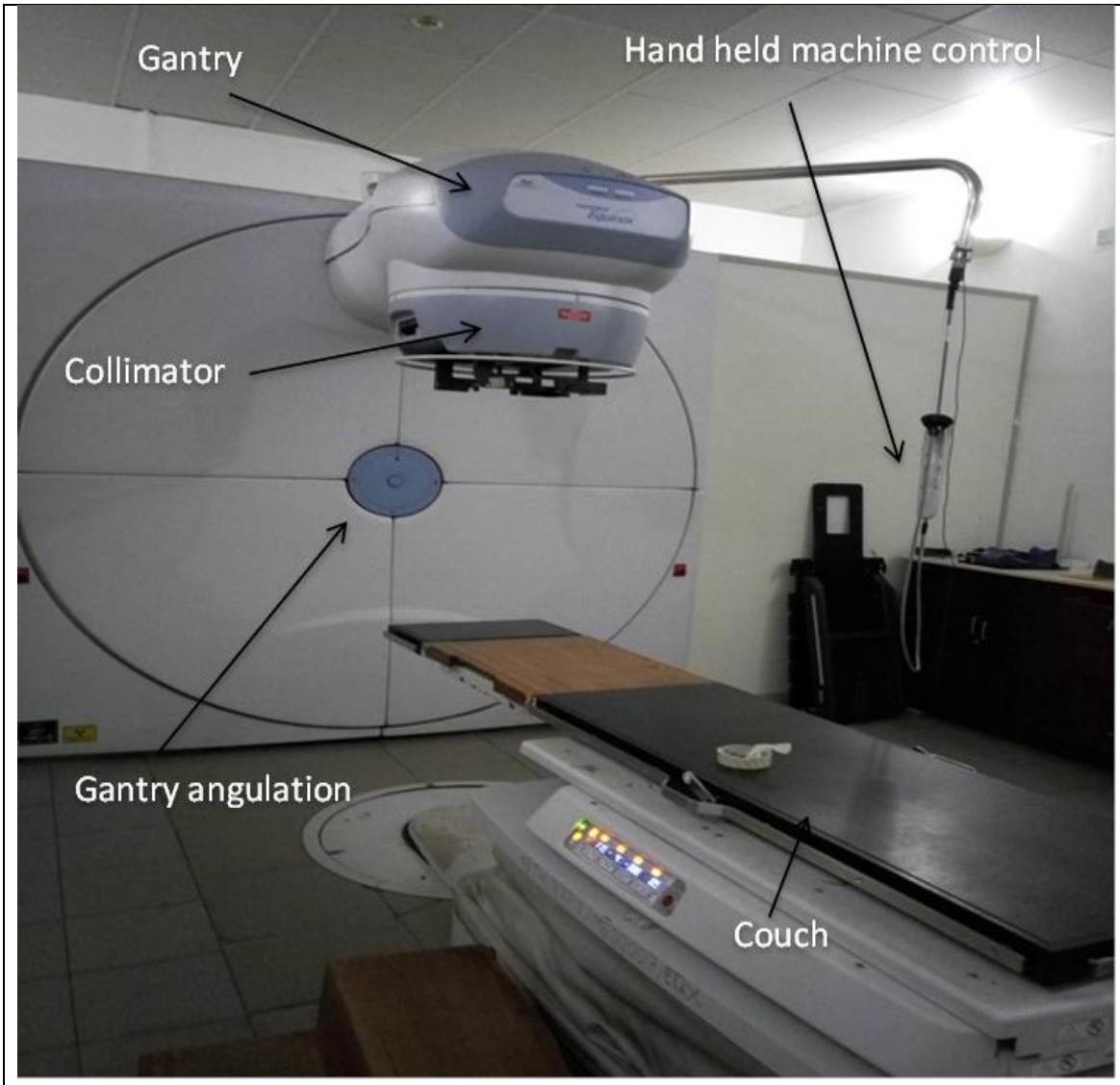


Figure 3.2: Theratron Equinox 100 cobalt-60 teletherapy machine

3.2.4 The Oncentra MasterPlan

Oncentra MasterPlan (Nucletron Corporation, Netherland, serial No: 0344, Year: 2012) shown in Figure 3.3, is the treatment planning system (TPS) in use at SGMC. This TPS uses pencil beam (PB) and collapsed cone (CC) algorithms for dose calculation. These algorithms are model-based type of algorithm [44]. The PB algorithm is based on a 2D convolution for volume integration. It accounts for heterogeneities by equivalent path length corrections for the primary dose contribution and a 1D convolution along fan lines with an exponential fall off of the scattered radiation [45].

On the other hand, for the CC algorithm, a ray-trace procedure through the irradiated object is used to obtain total energy released in matter (TERMA) at all points within the dose calculation matrix. The TERMA is separated into a primary component (collision kerma) and a scatter component, each of which are transported separately along the predefined 106 lines from the point of interaction [46].

Oncentra MasterPlan provides users in the clinics a high degree of flexibility in combination with many advanced planning abilities. It has in-built contouring tools, powerful dose calculation algorithms and innovative plan review components. It is fully featured external beam planning system with most advanced planning techniques capabilities.

Figure 3.3: Oncentra MasterPlan in use for breast case planning

3.2.5 Prowess Panther 3D planning system (version 4.6)

At KBTH, Prowess Panther version 4.6 treatment planning system (Prowess Inc., Ridgewood Drive, Suite 20 Chico, California 95973, USA) is in use. The prowess Panther is a 3D- radiation therapy treatment planning system designed to run on a Microsoft Windows (PC). The system uses collapsed cone convolution superposition (CCCS) calculation to determine dose distribution within a patient from external photon beams [47]. Figure 3.4 shows computer units with prowess panther 3D planning system.

Figure 3.4: Prowess Panther Version 4.6 TPS

3.2.6 Computed Tomography

Siemens SOMATOM Emotion 16 (Siemens, Syngo CT 2009E, Germany) shown in Figure 3.5 was used in this study. The equipment is a whole body, multi-slice, spiral CT scanner that produces highly detailed three –dimensional images of the body. It is equipped with modern clinical applications such as a slim, wide-open, high speed patient gantry and high power reserves. To perform image reconstruction and reduce noise, the scanner uses Iterative Reconstruction in Image Space (IRIS) technology. The Adaptive Signal Boost (ASB) in SOMATOM emotion is to improve weak signals in the course of high attenuation, while the Fully Assisting Scanner Technology (FAST) and the Combined Applications to Reduce Exposure (CARE) software help automate the imaging process and lessen the radiation dose delivered to patients [48].

Figure 3.5: Siemens, SOMATOM Emotion CT Scanner

3.2.7 Farmer type ionization chamber

Figure 3.6 shows the PTW cylindrical Farmer type ionization chamber (PTW Freiburg, Germany, S/N: 000820, Ref:TM30010-1, 2012) with sensitivity volume of 0.6 cc.

Figure 3.6: PTW Cylindrical Farmer type ion Chamber

The chamber was calibrated based on absorbed dose to water protocol with calibration factor of $N_{D,W} = 5.3852\times10^{7} Gy/C$ and following reference conditions: Temperature (T) = 20ºC, Pressure (P) =101.325 KPa, Relative humidity = 50 %, Chamber voltage polarity = +400 and ion collection efficiency = 100% [49].

3.2.8 PTW (UNIDOS Webline) Electrometer

PTW UNIDOS Webline Electrometer (PTW Freiburg, Germany, S/N: 000820) shown in Figure 3.7 is secondary standard reference class electrometer coupled with modern network features.

Figure 3.7: PTW Unidos Electrometer

This electrometer is an economical high quality dosimeter for universal use in radiation therapy and diagnostic radiology. It measures simultaneously integrated dose (charges) and dose rate (current). Ion chamber or solid-state detectors can be connected to it and it displays electrical charges in Coulomb (C).

3.2.9 Barometer

The precision Druck PACE1000 barometer (General Electric, UK, S/N: 3547193, 2012), pressure automated calibration equipment was used during measurements to correct the response of the ionization chamber for the effect of the difference that may exist between the standard reference pressure specified by the standards laboratory (101.3 kPa) and the pressure recorded in the facility under different environmental conditions. Figure 3.8 shows the Druck PACE1000.

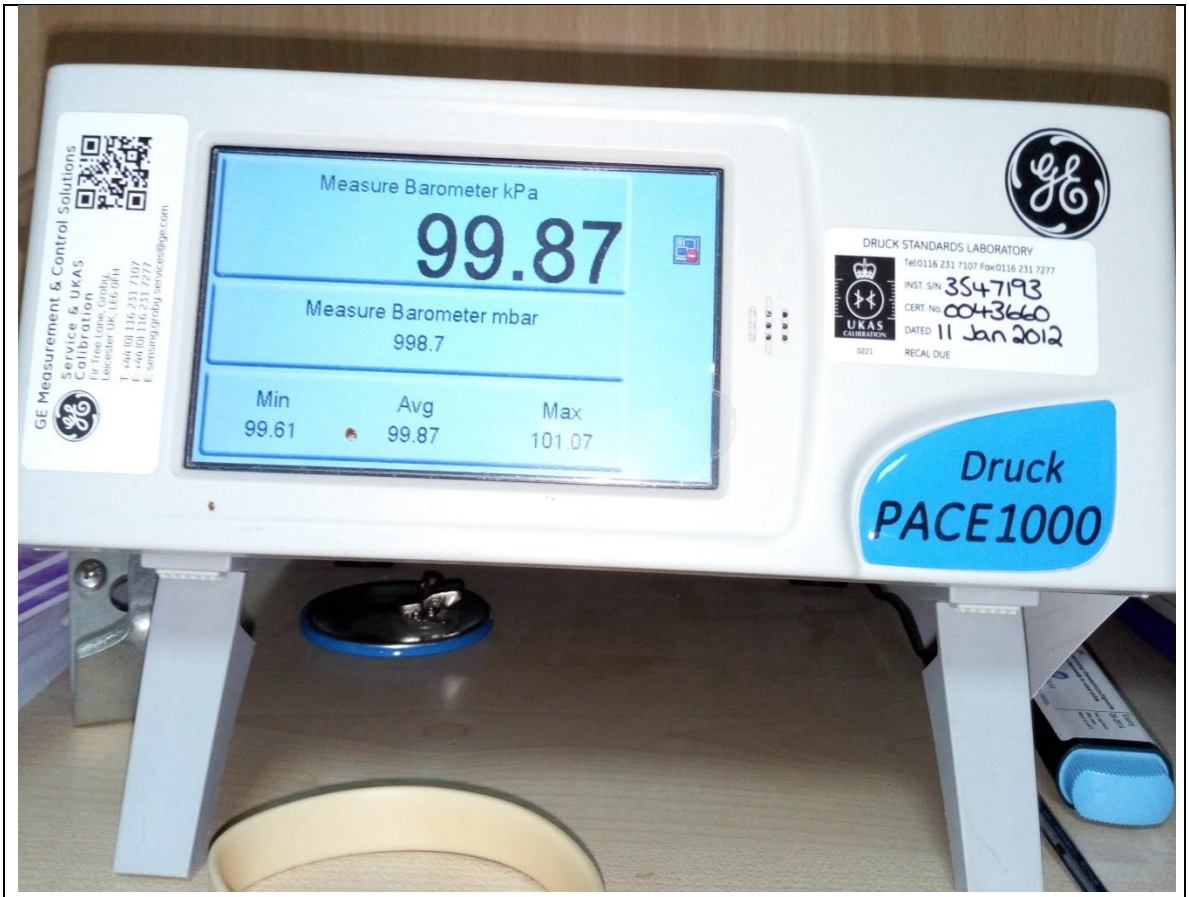


Figure 3.8: The druck PACE1000 Barometer

3.2.10 Thermometer

Testo 925 (Testo AG, UK) thermocouple thermometer shown in Figure 3.9 was used during charge measurements to correct the response of the ionization chamber for the effect of the difference that may exist between the standard reference temperature specified by the standard laboratory (20.0ºC) and the temperature recorded in the facility under different environmental conditions.

Figure 3.9: TESTO 925

3.2.11 PMMA and anthropomorphic Phantoms

Polymethylmethacrylate (PMMA) slab phantom also known under the trade name acrylic or perspex was used in this study for end-to end test. It is a tissue equivalent material available in 25 cm × 25 cm sections of varying thickness. Figure 3.10 shows PMMA slab phantom of thickness 10 cm and ion chamber hole at the center depth 5 cm from the surface. On the other hand, Figure 3.11 shows a whole body male anthropomorphic phantom. The phantom is molded from tissue-equivalent material.

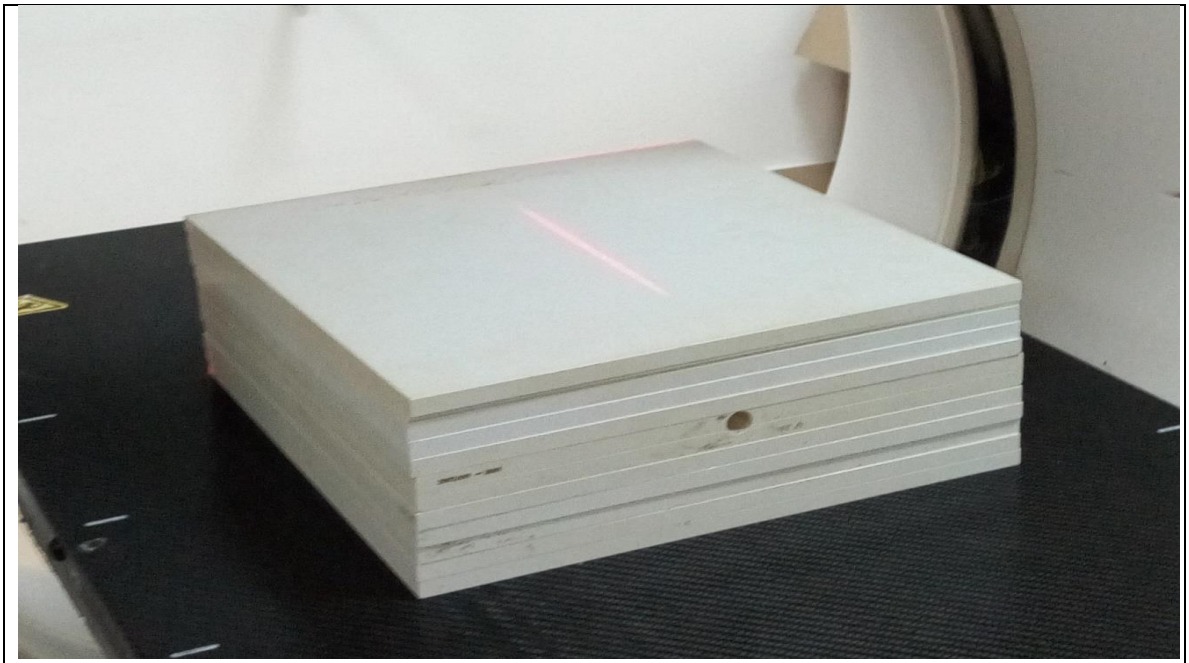


Figure 3.10: PMMA Slab Phantom

Figure 3.11: Anthropomorphic Phantom

3.2.12 Gafchromic films, Diode and Diode reader

Figure 3.12 show the detectors used for dose measurements in a phantom. The Gafchromic EBT3 medical dosimetry film (lot No: 04201601), Sun Nuclear QED (n-type) flat diode and Apollo 5 diode reader.

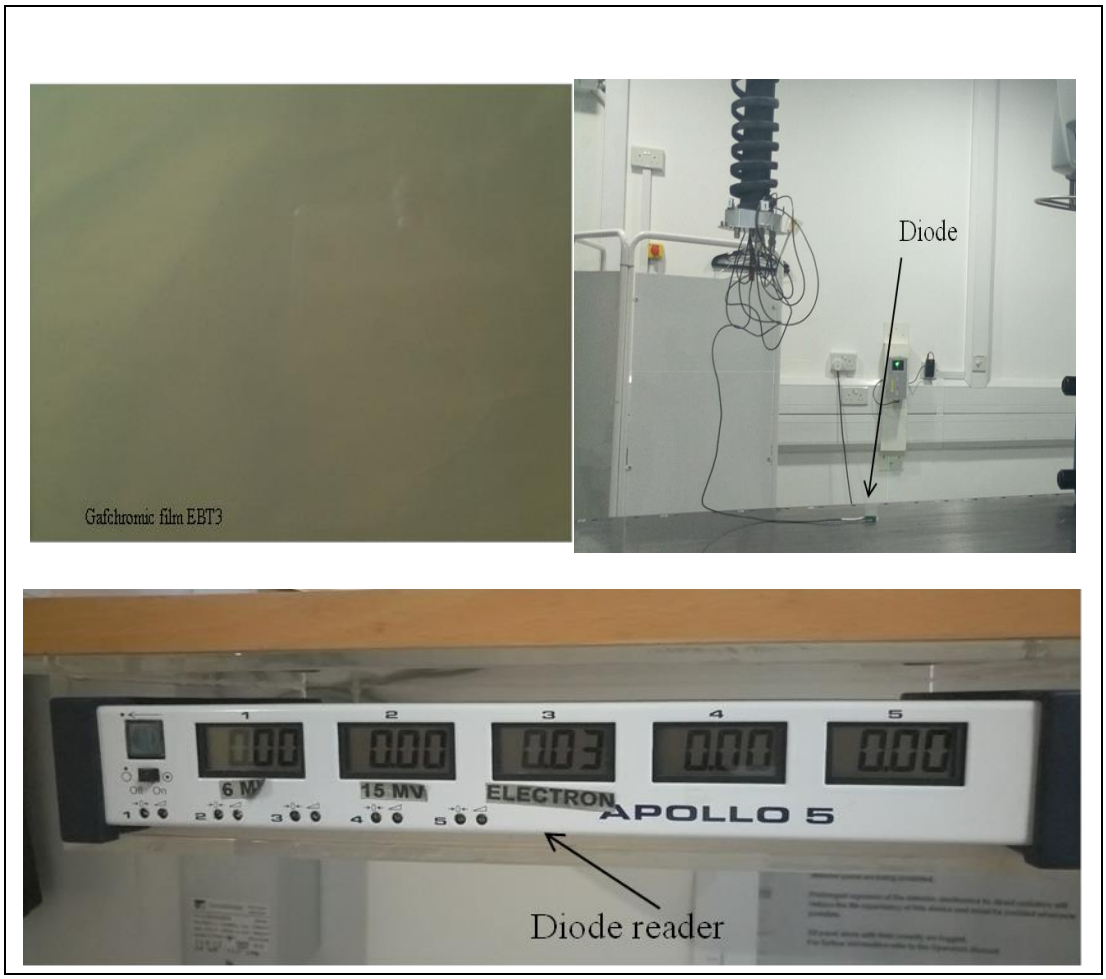


Figure 3.12: Detectors for dosimetry

3.3 METHODS

3.3.1 Patient selection and target definition

The three clinical sites of breast, prostate and lungs were chosen based on the most frequently registered cases for both males and females according to WHO 2012 database. Furthermore, nature of the case such as superficial and deep-seated tumor was also considered. Based on that, breast case and prostate case were identified as the most prevalent among females and males as well as being superficial and deep-seated tumors respectively. On the other hand, lung case was considered to be for both sexes and owing to its dose inhomogeneity variation [49].

The retrospective CT scans of three patients from the European Society for Radiotherapy and Oncology (ESTRO) obtained and used in this study are shown in Figure 3.13. The required and requisite target and normal tissue volumes on the axial CT images were pre-contoured.

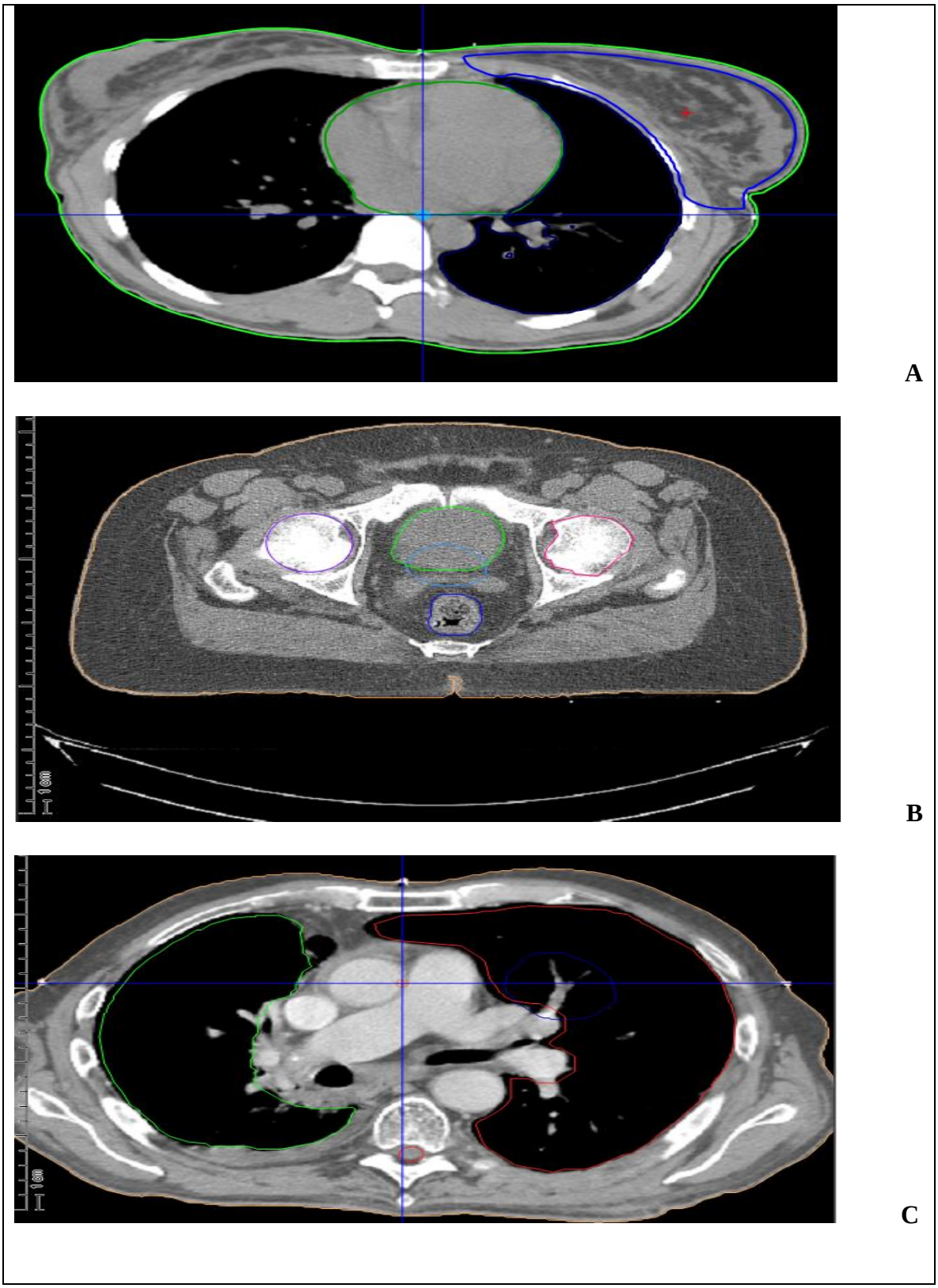


Figure 3.13: Retrospective CT slices (**A**) Breast (**B**) Prostate (**C**) Lung

3.3.2 Breast case

For this comparison, a patient with left-sided breast cancer was considered. A dose of 50 Gy in 25 daily fractions of 2 Gy given in 5 weeks was prescribed for both treatment machines with a planning goal of 95% of the planned tumour volume (PTV) to be covered by 95% of the prescription dose. Plans were created for cobalt-60-based using opposing 15 degrees wedged tangential fields and 12 field in field tangential beams for linac-based (6 MeV photons). The dose was normalized to 100 % at isocenter (thus absolute dose 50 Gy corresponds to the relative dose of 100%). Dose constraints, based on Quantitative Analysis of Normal Tissue Effects in the Clinic (QUANTEC) summary in Appendix A, were: Heart (mean dose $\leq$ 26 Gy, D_{max} = 40 Gy), Left-Lung ($V_{20\ Gy} \leq 30$ %). Table 3.1 summarizes the beam parameters for breast case while Figure 3.14 and Figure 3.15 show the beam set-up for both cobalt-60-based and linac-based breast plans.

Table 3.1: Breast plan beam parameters

Unit	No of fields	Set-up	Gantry angles	Algorithm	Beam modifier
Cobalt-60	2	SSD	308.2^0, 135.7^0	CS	15^0 Wedges
Linac	12 (F-in-F)	SSD	310^0, 130^0	CC	MLCs

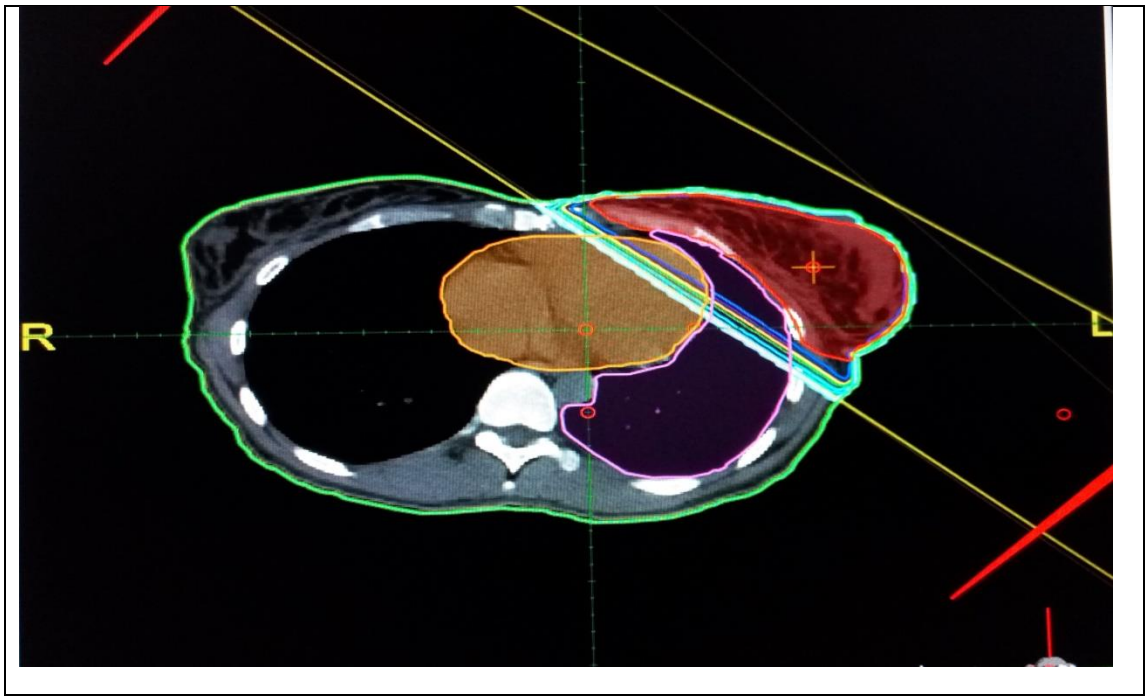


Figure 3.14: Cobalt-60 beam set-up for breast plan

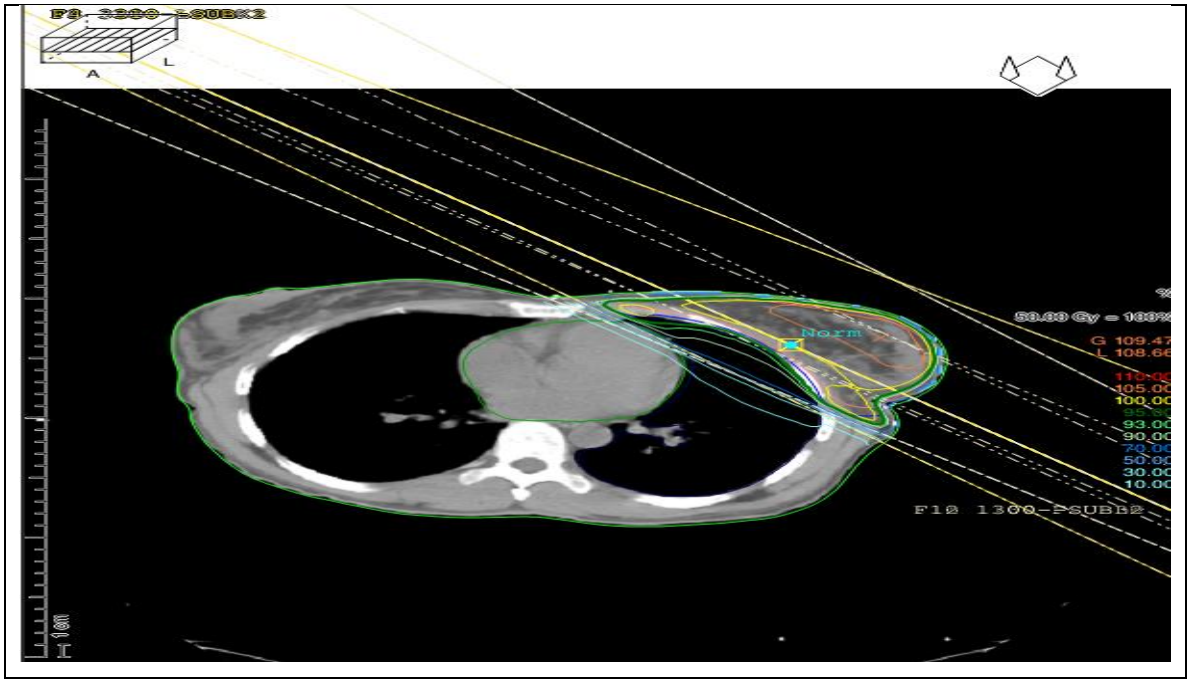


Figure 3.15: Linac beam set-up for breast plan

3.3.3 Prostate case

The prescribed dose to the PTV was 78 Gy in daily fractions of 2 Gy for 8 weeks. A 4-fields beam plan of gantry angles 0^0, 90^0, 180^0, 270^0 was prepared using linac (15 MeV photons) with each beam weighted equally. This was compared with a 4-fields beam plan of gantry angles 0^0, 90^0, 180^0, 270^0 and a 5-fields beam plan of gantry angles 0^0, 90^0, 270^0, 120^0, 240^0 cobalt-60 (1.25 MeV) prepared using conformal blocks. Table 3.2 shows a summary of beam parameters for prostate plans. On the other hand, Figure 3.16 and Figure 3.17 show the beam arrangement for both cobalt-60-based and linac-based prostate plans. Dose constraints for OAR are shown in Table 3.3, which were based on QUANTEC summary in Appendix A.

Table 3.2: Prostate plan beam parameters (wg=Wedge, OF=Open Field)

Unit	No of fields	Set-up	Gantry angles	Algorithm	Beam modifier
Cobalt-60	4	SSD	0^0, 90^0, 180^0, 270^0	CS	(OF,15^0 wg,15^0wg,OF)
	5	SSD	0^0, 90^0, 270^0, 120^0, 240^0	CS	(OF,15^0wg,15^0wg,OF,OF
Linac	4	SSD	0^0, 90^0, 180^0, 270^0	CC	MLCs

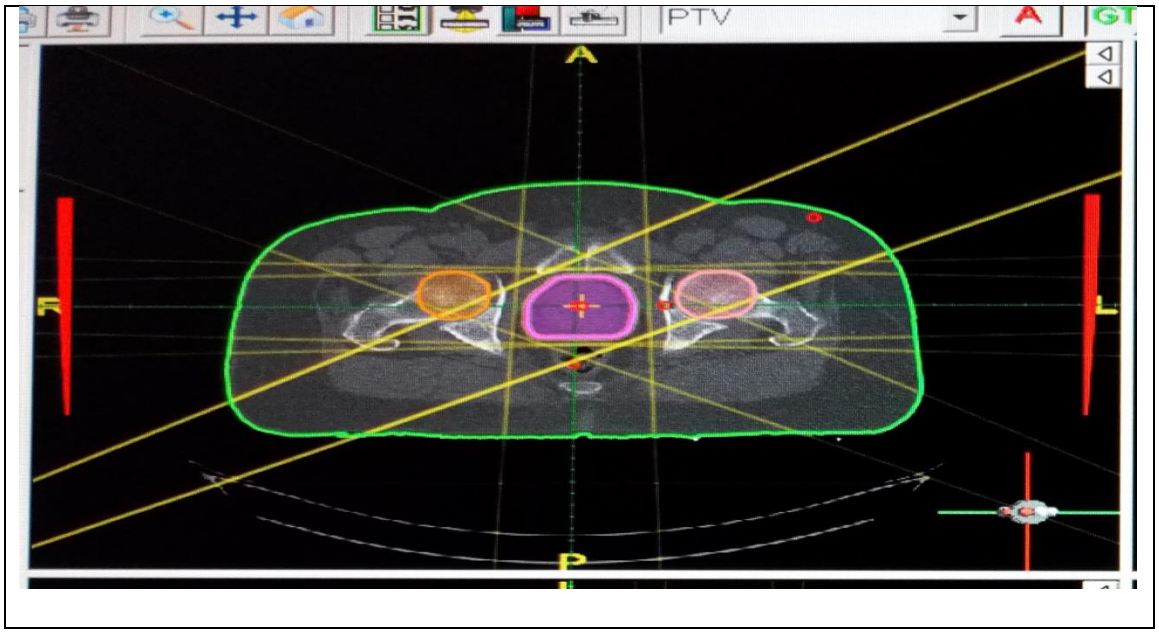


Figure 3.16: A 5-Field beam set-up plan for cobalt-60 (Ant, Lt.Lat, Rt.Lat, Lt.Posterial oblique, Rt.Posterial oblique beams)

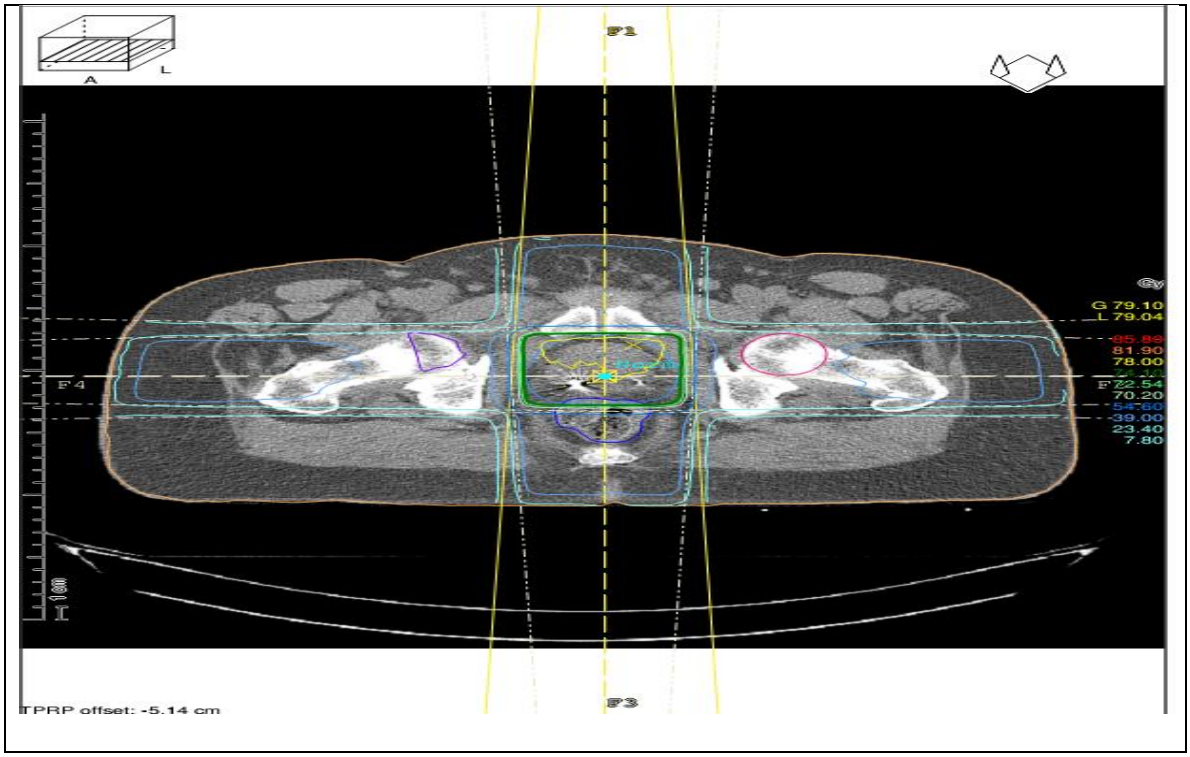


Figure 3.17: A 4-Field beam set-up plan of a prostate plan for linac

Table 3.3: Dose-volume constraints adopted for prostate planning study

($\mathbf{V_x}$ = Volume getting x-Dose in Gy of the prescribed dose, $\mathbf{D_{max}}$ = maximum Dose)

Structure	Constraints
PTV	≥95% 0f the prescribed dose
Bladder	V65≤35%
	V70≤25%
	V75≤15%
	V80≤15%
Rectum	V50≤50%
	V60≤35%
	V65≤25%
	V70≤20%
	V75≤15%
Lt. Femur	D_{max} = 55 Gy
Rt. Femur	D_{max} = 55 Gy

3.3.4 Lung case

The prescribed dose was 66 Gy in 2 Gy per fractions for 7 weeks. The planning dose prescription on the target required that at least 95% of the PTV had to receive not less than 95% of the prescribed dose. Dose calculations were done with the collapsed cone convolution superposition algorithm (CCCS) of Prowess Panther V 4.60 and pencil beam (PB) of the Oncetra masterPlan treatment planning systems. Planning on cobalt-60 was done with three conformal fields (3-Fields) of gantry angles 322.1^0, 38.6^0, and 180^0. Each beam has a 30 degree wedge and blocks as beam modifier. Similarly, for linac (6 MeV photons), the plan was also done with three conformal fields (3-Fields) of gantry angle

90^0, 137^0, 356^0 and shaped with 60 degrees motorized wedges. Figure 3:18 shows the beam set-up for the lung plan.

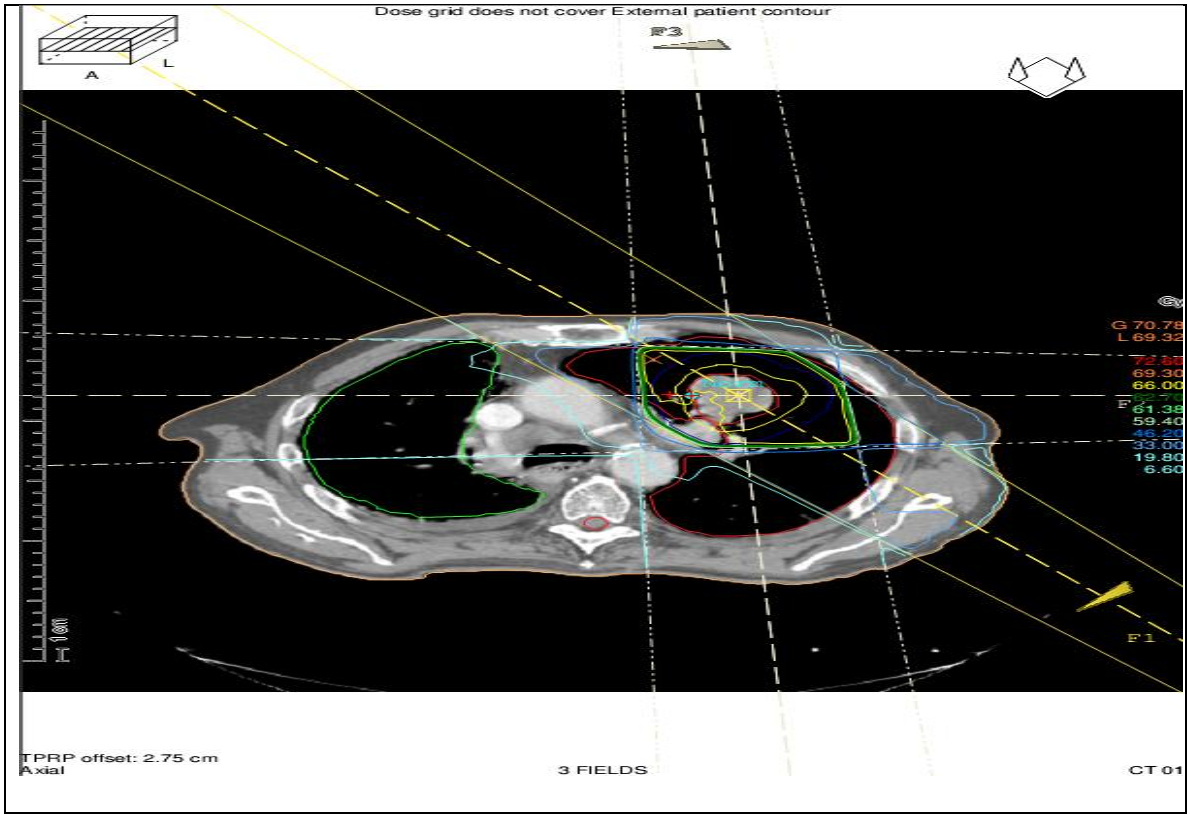


Figure 3.18: Beam set-up for Lung plan

The main OAR structures and constraints were: Heart (Mean dose < 26 Gy, $V_{30\ Gy}$ < 46%, D_{max} = 40 Gy), Spinal cord (D_{max} = 50 Gy), Contralateral Lung ($V_{20\ Gy}$ ≤30%). These were obtained from QUANTEC summary in Appendix A.

3.3.5 Plan comparisons

Analytical comparisons were performed among the plans. This involved evaluation of the following parameters extracted from dose–volume histogram (DVH): homogeneity index (HI), conformity index (CI), the minimum (D_{min}), maximum (D_{max}) and mean dose (D_{mean}) to volume of interest for breast, prostate and lung. Further evaluation and comparison of the treatment plans was also made at surrounding organs at risk by referring to the Quantitative Analysis of Normal Tissue Effects in the Clinic (QUANTEC) in Appendix A.

Calculation of the conformity index (CI) and homogeneity index (HI) was done using RTOG formulae shown in equations 2.1 and 2.2 respectively from chapter two [9, 11, 21].

3.3.6 Quality Assurance (QA) of the treatment planning in EBRT

Quality assurance (QA) is mandatory throughout the planning process for EBRT in order to minimize undue exposure.

End-to-end test to determine machine out-put as well as in-vivo dosimetry (IVD) for verification of the plans were carried out in this study for quality assurance.

The end-to-end test involved the use of PMMA phantom whereby the following steps were followed:

Firstly, CT scans of the phantom were acquired using Siemens SOMATOM Emotion 16 CT scanner.

Secondly, axial CT images of the phantom were uploaded into the respective treatment planning systems. Templates of the patient specific treatment plans were created and placed on the phantom. Calculation point was placed within the phantom to correspond with effective point of measurement of the detector that was used to measure dose within the phantom. The measured dose distribution within the phantom was determined for each plan as well as that of the calculation point (depth= 5 cm). Durations (treatment times/monitor units) of treatment provided by the treatment planning systems were recorded together with the calculated dose at depth 5 cm for each plan. The treatment plans created for the phantom were replicated on the requisite treatment machine and the dose at depth = 5 cm measured for each plan. The measured doses were then compared to their calculated counterparts obtained during treatment planning. Figure 3.19 show a step by step for end-to-end test.

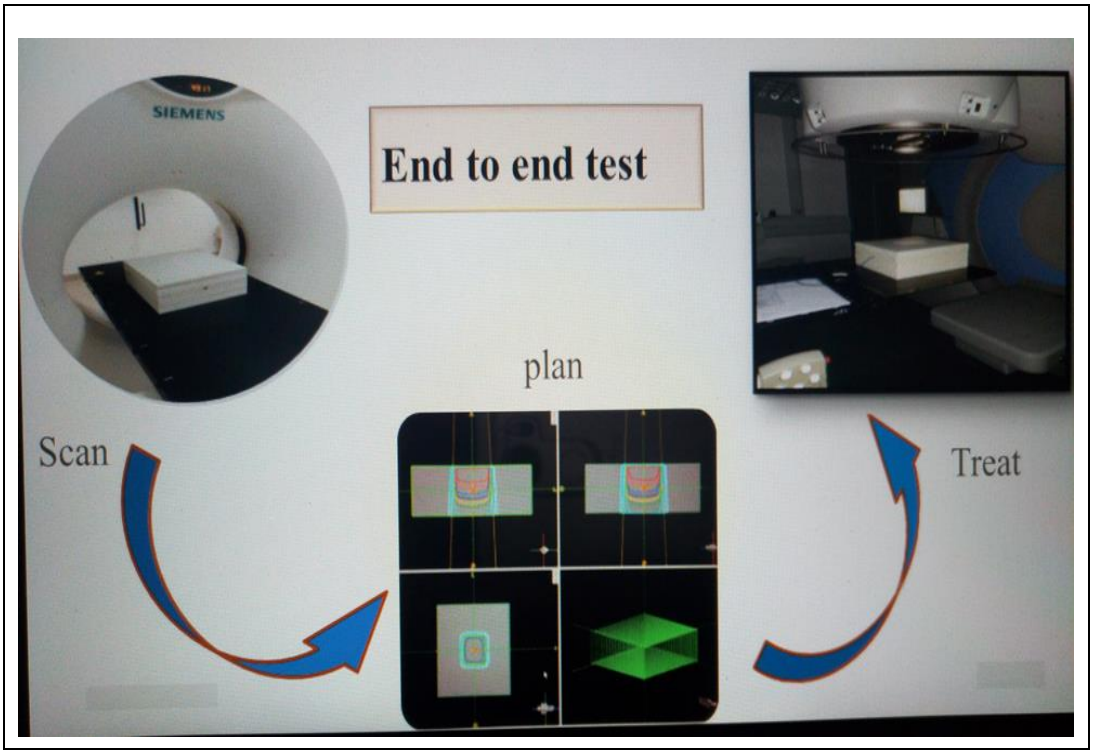


Figure 3.19: End to end test using PMMA Phantom

Plan verification also called In-vivo dosimetry (IVD) was conducted using anthropomorphic phantom and dosimetry detectors as shown in Figure 3.20. The phantom was scanned on Siemens SOMATOM Emotion 16 CT-scanner and two treatment sites, pelvis and thorax, were planned with beams energy of 6 MeV and 15 MeV for linac while 1.25 MeV for cobalt-60. A dose of 2 Gy was prescribed at isocenter depth 10 cm, field side 10 x 10 cm^2, SSD of 90 cm. The phantom was then irradiated and dose measured using diode and Gafchromic films at SGMC and NCRNM centers respectively. Comparison of measured dose with the planned dose was then done to detect major errors, assess the clinically relevant differences between the planned and delivered doses.

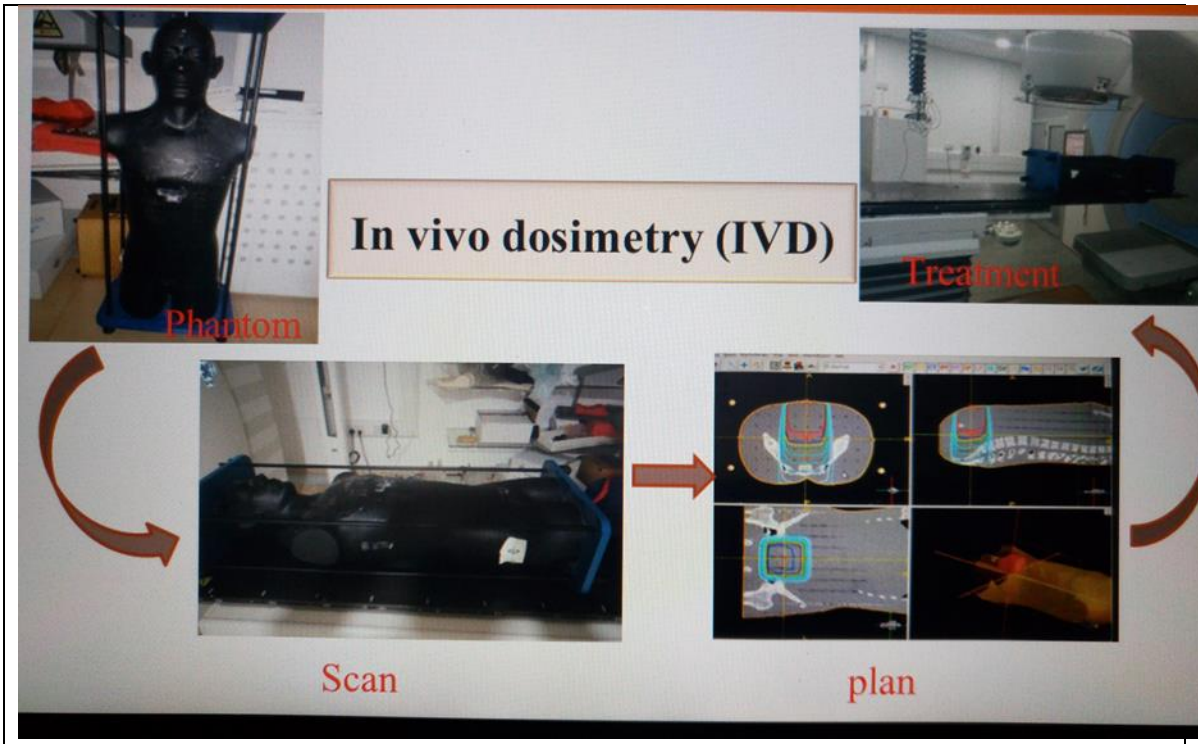


Figure 3.20: In vivo dosimetry (IVD) with anthropomorphic phantom

Chapter Four

RESULTS AND DISCUSION

4.1 Introduction

Included in this chapter are the results of the work done and discussions related to these results. A comparison of plan dose information such as maximum dose, minimum dose, mean dose, CI and HI for three conformal radiotherapy cases (breast, prostate and lung) has been established and presented between telecobalt machine and linac machine. Furthermore, comparison of dose constraints to OARs between the two plans as well as results of plan delivered dose on their respective treatment machines has also been summarized.

4.2 Comparison of CI, HI, D_{max}, D_{min}, D_{mean} and dose to OARs between Telecobalt and Linac 3D- CRT plans

The results of the study are presented based on the following parameters extracted and calculated from dose-volume histograms: the CI, HI, D_{max}, D_{min}, D_{mean} as well as dose to critical organs for each case.

4.2.1 Breast case

Figure 4.1 and Figure 4.2 shows DVH of the PTV and OARs (i.e. heart and left lung) for the breast plan generated by cobalt-60 Prowess Panther V6.4 and linac Oncentra MasterPlan treatment planning systems respectively. On the other hand, Table 4.1 and Table 4.2 summarize the comparison of dosimetric data extracted from those DVH for the PTV and the OARs respectively between cobalt-60-based plan and linac-based plan for breast case.

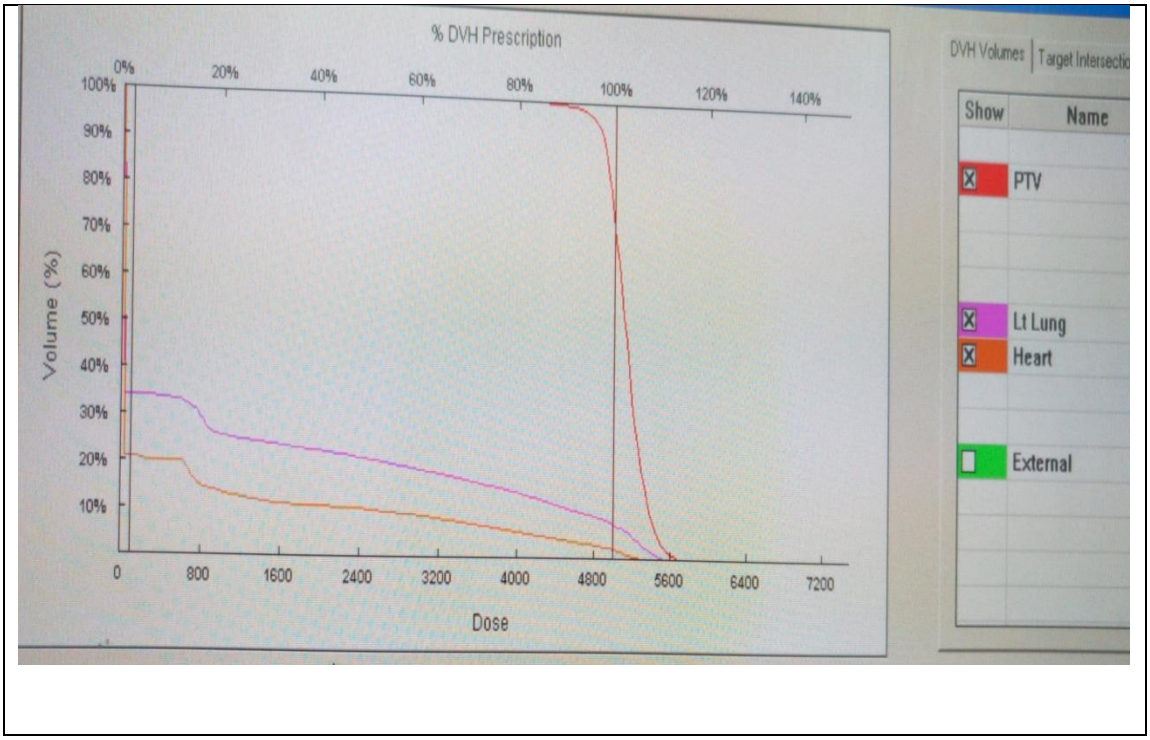


Figure 4.1: DVH of cobalt-60-based plan for breast case

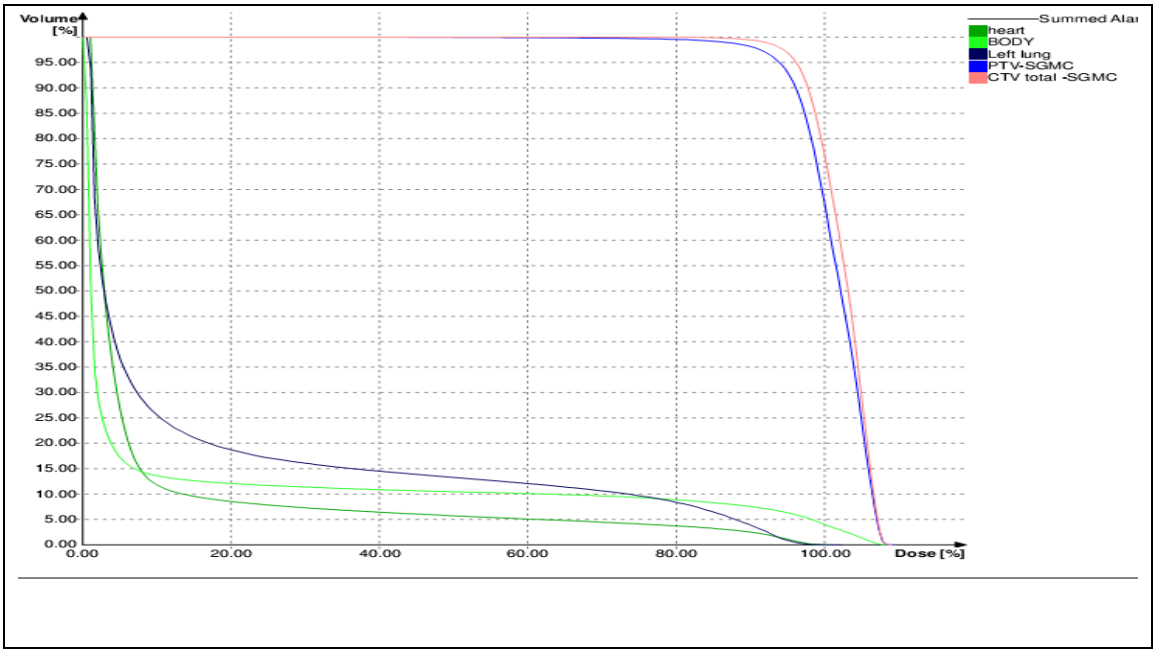


Figure 4.2: DVH of linac-based plan for breast

Table 4.1: Comparison of dosimetric parameters between cobalt-60-based and linac based 3D-CRT treatment plan for breast case

Structure	Parameter	Cobalt-60	Linac
PTV	Volume (cc)	713.31	713.31
PTV (50 Gy)	D_{max} (Gy)	57.26	54.55
	D_{min} (Gy)	0.00	18.57
	D_{mean}(Gy)	51.09	51.13
	CI	0.9705	0.9303
	HI	1.1452	1.0910

Table 4.2: Comparison of OAR dose evaluation between cobalt-60-based and linac-based plan for breast case

Structure	Constraints	Cobalt-60	Linac
Heart	Mean dose<26 Gy	5.22	4.34 Gy
	V30<46%	8.80%	4.89%
	V25<10%	10.00%	5.60%
Ipsilateral lung	V20<30%	22.80%	14.66%

The results in Table 4.1 show that the maximum dose ($D_{max,}$) and mean dose (D_{mean}) to the PTV were slightly different between cobalt-60 and the linac plan. However, the minimum dose (D_{min}) for cobalt based plan was 0.00 Gy lower compared to 18.57 Gy for linac-based plan. The high D_{min} for linac-based plan was as a result of high energy which increases the build-up and is compensated by use of bolus. So bolus is used when treating

superficial tumors such as breast case to improve dose distribution and reduce skin sparing effect of high energy beams.

The calculated CI of the PTV was 0.9705 for cobalt-60-based plan and 0.9303 for linac-based plan. The results show that cobalt-60-based plan yielded superior conformity compared with linac-based plan since the CI was very close to ideal value 1 according to RTOG protocol. The cobalt-60 breast plan was more conformal because of low energy beams which studies have shown that low energy beams are favourable for treatment of superficial tumors [32]. The CI indices for both plans were within the recommended RTOG protocol of minor violation as summarized in Table 2.2.

For HI, the values obtained were 1.1452 and 1.0910 for cobalt-60-based and linac-based plans respectively and with linac-based plan having better dose homogeneity than cobalt-60-based plan as its value was close to ideal value of 1 according to RTOG protocol. The HI values for both plans were within the range of 1 and ≤ 2 hence complied with the RTOG protocol as illustrated in Table 2.3.

Very significant differences were observed between the two plans for organ at risk sparing doses in Table 4.2 with coalt-60-based plan having higher doses to organ at risks than linac-based plan. Hence linac-based plan had advantage in terms of sparing organ at risk than cobalt-60-based plan. However, those doses to OARs for both plans were all within the acceptable agreement criteria according to dose-volume constraints adopted for this planning from QUANTEC summary in Appendix A.

4.2.2 Prostate case

The maximum dose (D_{max}), minimum dose ($D_{\min}$), mean dose (D_{mean}), conformity index (CI) and homogeneity index (HI) are presented for comparison between cobalt-60-based and linac-based plans in Table 4.3, while Table 4.4 present comparison of doses to organs at risk . These parameters have been extracted from the DVH in Figure 4.3 and Figure 4.4 for both cobalt-60-based and linac-based plans for prostate case respectively.

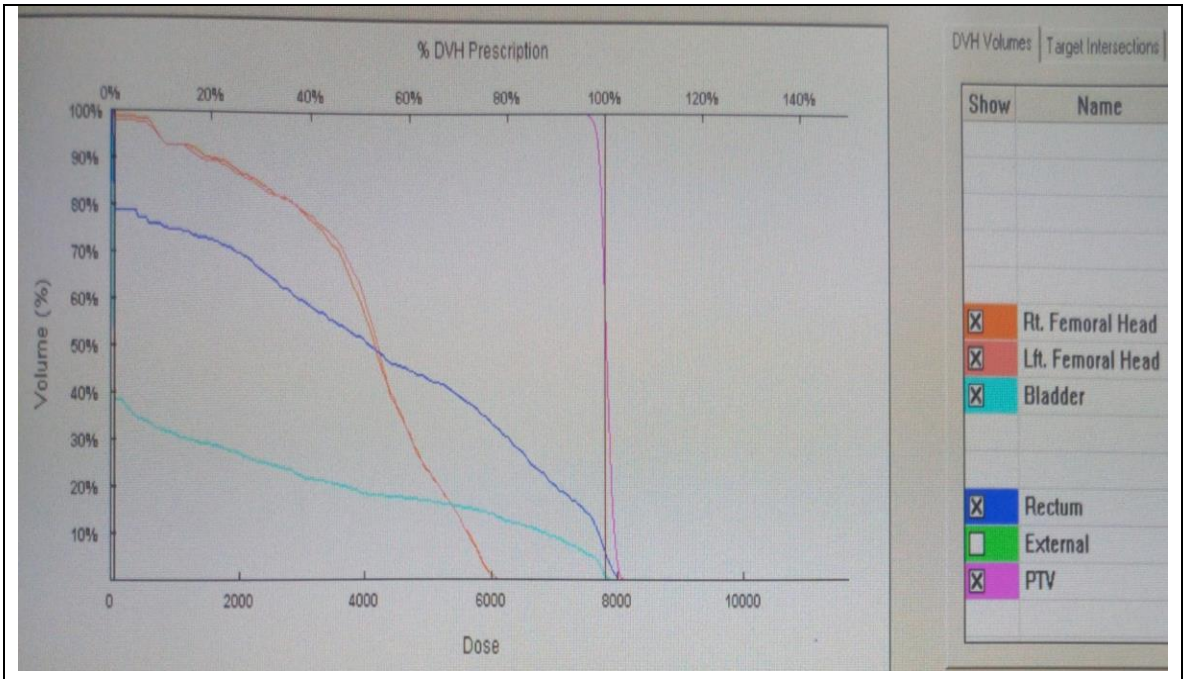


Figure 4.3: DVH of cobalt-60-based plan for prostate case

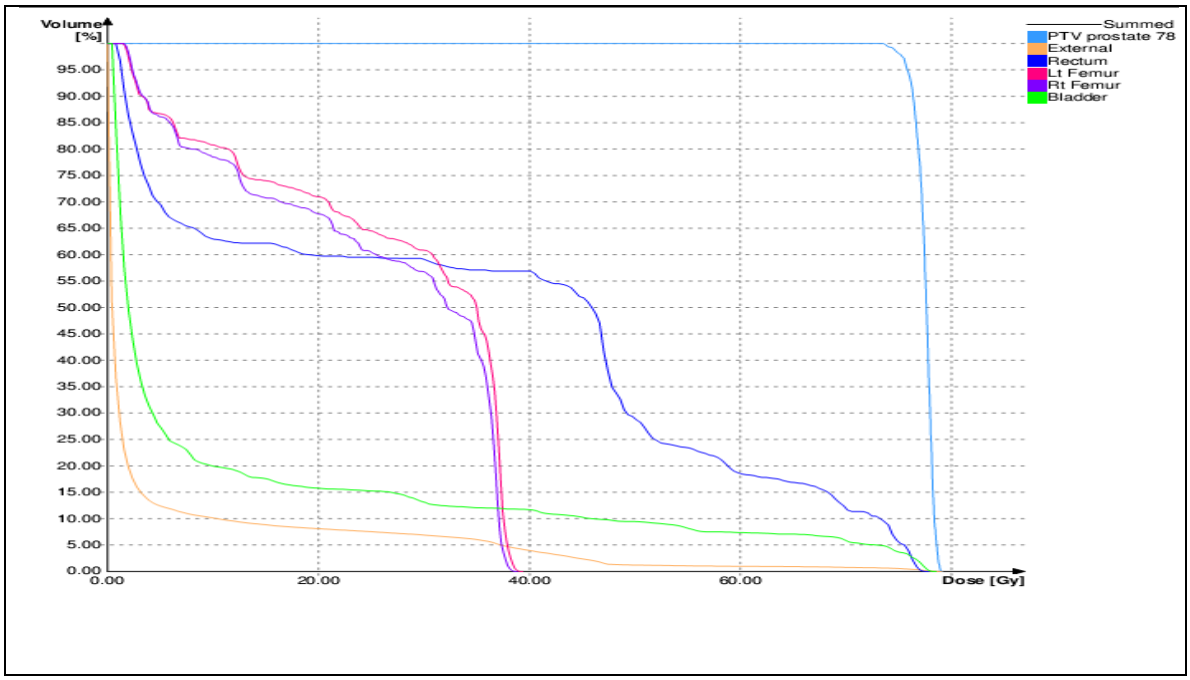


Figure 4.4: DVH of linac-based plan for prostate case

Table 4.3: Comparison of dosimetric parameters between cobalt-60-based and linac based plan for prostate case

Structure	Parameter	Cobalt-60		Linac
		4-Fields	5-Fields	4-Fields
PTV	Volume (cc)	105.17	105.17	105.17
PTV (78 Gy)	D_{max} (Gy)	79.76	80.85	79.10
	D_{min} (Gy)	72.96	73.73	73.57
	D_{mean}(Gy)	76.54	77.61	77.57
	CI	0.9881	0.998	0.9948
	HI	1.0226	1.0365	1.0141

Table 4.4: Dose to OARs for prostate case between cobalt-60-based and linac-based plans

Structure	Constraints	Cobalt-60		Linac
		4-Field	5-Field	
Rectum	V50<50%	59.20%	37.60%	29.04%
	V60<35%	35.20%	27.20%	18.58%
	V65<25%	24.40%	20.40%	16.82%
	V70<20%	16.00%	14.00%	11.79%
	V75<15%	8.00%	7.00%	5.75%
Bladder	V65<50%	8.80%	10.00%	6.94%
	V70<35%	6.80%	7.60%	5.75%
	V75<25%	4.40%	4.80%	3.45%
	V80<15%	0%	0%	0%
Lt. Femur Head	D_{max} = 55Gy	35.41 Gy	57.96 Gy	39.09 Gy
Rt. Femur Head	D_{max} = 55Gy	35.49 Gy	56.91 Gy	38.58 Gy

The results show no significant difference between cobalt-60-based plan and linac-based plan for D_{max}, $D_{\min}$ and D_{mean}. It can also be observed that by increasing the number of fields for a cobalt-60-based plan from 4-fields to 5-fields makes the plan to be more comparable to that of linac-based plan.

The calculated CI was 0.9881, 0.9980 for 4-fields and 5-fields cobalt-60-based plans respectively and 0.9948 for linac-based plan. There was no significant difference observed for CI between 5-fields cobalt-60-based and linac-based prostate plan. The HI values obtained were 1.0226, 1.0365 for 4-fields and 5-fields cobalt-60-based plan respectively and 1.0141 for linac-based plan. Similarly, the HI value show no significant

difference between cobalt-60-based plan and linac-based plan only that the HI value for linac-based plan was closer to ideal RTOG value of 1 summarized in Table 2.3. The dose conformity and dose homogeneity was within the acceptable ranges of RTOG protocol between cobalt-60-based and linac-based prostate plans.

The comparison of dose to OARs between cobalt-60-based plan and linac-based plan for the prostate case in Table 4.4 shows that the rectum received higher doses for 4-fields Cobalt-60-based plan than linac-based as observed from the parameters V50 = 59.20%, V60 =35.20%, V65 = 24.40% and V70 = 16.00%. However, as the number of fields increased from 4-fields to 5-fields the doses to rectum decreases but were still higher than those of linac-based plan.

Doses to bladder show no much significant differences between cobalt-60-based plans and linac-based plan. However, in contrast, doses to rectum and femur heads increased as the number of fields increased from four to five in cobalt-60-based plan. The results further show that both left and right femur heads receives more doses either for cobalt-60-based plan or linac-based plan. The 4-fields cobalt-60-based plan offered a better chance of femur heads sparing than the 5-field as well as the linac-based plans. This agree with results from Adams and Warrington (2008) study which established that this increase of doses to femur heads is as a result of lateral beams and can be minimized by less weighting or place wedges to the lateral beams [20].

4.2.3 Lung case

Table 4.5 illustrates the comparison of treatment parameters between cobalt-60-based and linac-based 3D-CRT plan for lung case extracted from DVH in Figure 4.5 and Figure 4.6.

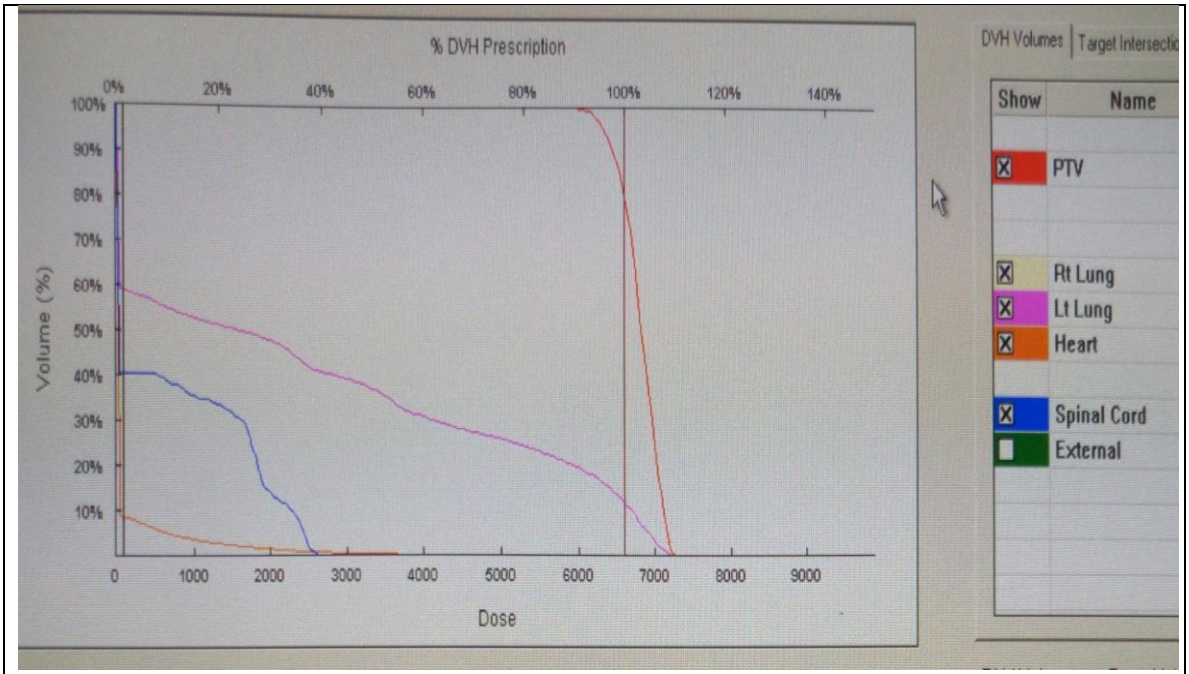


Figure 4.5: DVH of cobalt-60-based plan for lung case

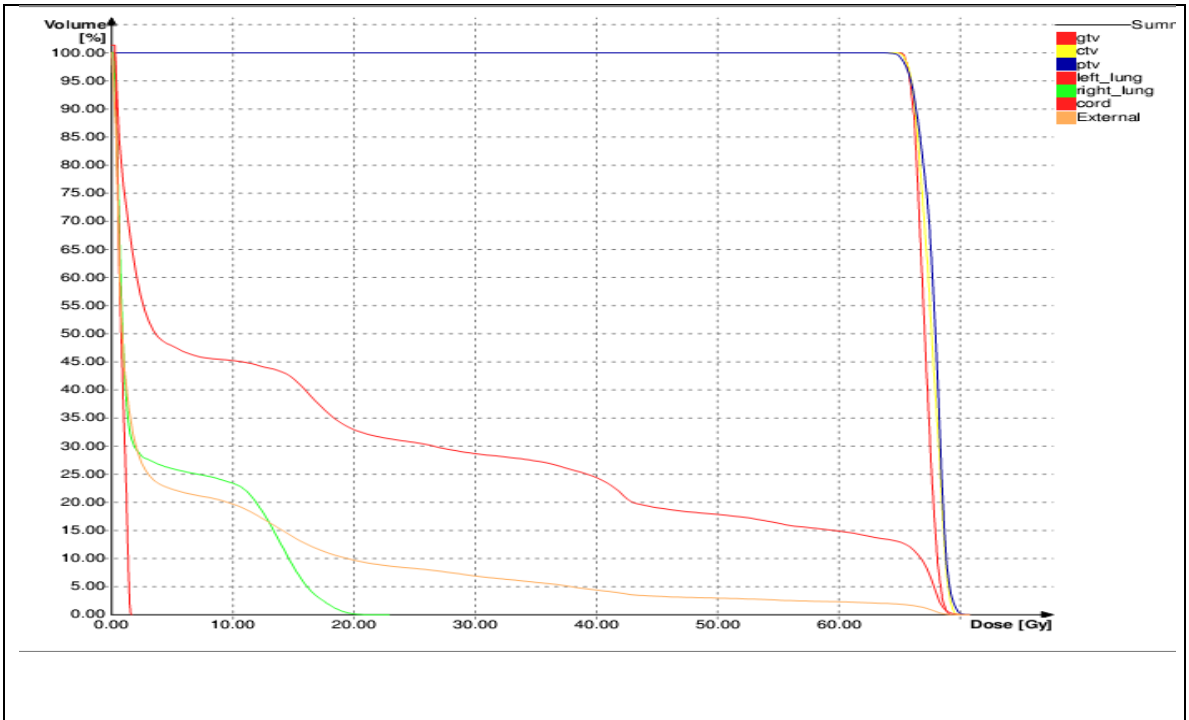


Figure 4.6: DVH of linac-based plan for lung case

Table 4.5: Comparison of dosimetric parameters between cobalt-60-based and linac-based plans for lung case

Structure	Parameter	Cobalt-60	Linac
PTV	Volume (cc)	206.51	206.51
PTV (66 Gy)	D_{max} (Gy)	72.33	70.50
	D_{min} (Gy)	55.49	64.18
	D_{mean}(Gy)	67.82	67.83
	CI	0.9604	1.0005
	HI	1.0960	1.0682

Dosimetric outcomes for planning target coverage in Table 4.5 were slightly different between cobalt-60-based and linac-based treatment plans with D_{max} = 72.33 Gy, D_{min} = 55.49 Gy, D_{mean} = 67.82 Gy versus D_{max} = 70.50 Gy, D_{min} = 64.18 Gy, D_{mean} = 67.83 Gy respectively. Conformity index (CI) for cobalt-60-based plan was 0.9604 while for linac-based plan was 1.0005. The CI for linac-based plan was very close to the ideal RTOG value of 1 illustrated in Table 2.2, which means that the prescription isodose line was overlapping with the PTV. The higher conformal on linac-based plan is as a result of energy used which have been proved to be suitable for planning deep seated tumor and organs having different tissue in homogeneities such as the lung case.

For homogeneity index (HI), the difference between cobalt-60-based and linac-based 3D-CRT lung plan can also be seen distinctly in the Table 4.5. The HI values were 1.0960

and 1.0682 for cobalt-60-based and linac-based plans respectively. The linac-based plan had a better dose homogeneity since the HI value obtained was close to the ideal RTOG protocol of 1 adopted for this study in Table 2.3.

The summary of doses to OAR between coalt-60-based and linac-based treatment plans for lung case is illustrated in Table 4.6.

Table 4.6: Doses to the organs at risk between cobalt-60-based and linac-based plans for lung case.

Structure	**Constraints**	**Cobalt-60**	**Linac**
Heart	Mean dose<26 Gy	11.10 Gy	1.25 Gy
	V30<46%	0.40%	0%
	V25<10%	0.80%	0%
Spinal cord	D_{max} = 50 Gy	25.92 Gy	1.58 Gy

For both cobalt-60-based plan and linac-based plan, the dose to organs at risk can be tolerated according to QUANTEC. For example, the mean dose to the heart was 11.10 Gy for cobalt-60-based and 1.25 Gy for linac-based which was still below 26 Gy. The V30 and V25 to the heart were all 0% for linac-based compared to cobalt-60-based which were 0.40% and 0.80% but still less than 46% and 10% total volume of the heart respectively. The D_{max} of spinal cord was below 50 Gy with 1.58 Gy for a linac-based plan and 25.92 Gy for cobalt-60-based plan. The results have shown that linac-based plan also offers a greater chance of sparing OAR than cobalt-60-based plan for lung case.

4.2.4 Summary of CI and HI results between cobalt-60 and linac-based 3D-CRT for selected cases

Figure 4.7 and Figure 4.8 summarize the results of treatment indices for the three selected cases between cobalt-60-based and linac-based conformal treatment plans where the CI value of 1 is ideal dose conformity and also HI value of 1 is ideal dose homogeneity for the plan according to RTOG protocol illustrated in Table 2.2 and Table 2.3 respectively.

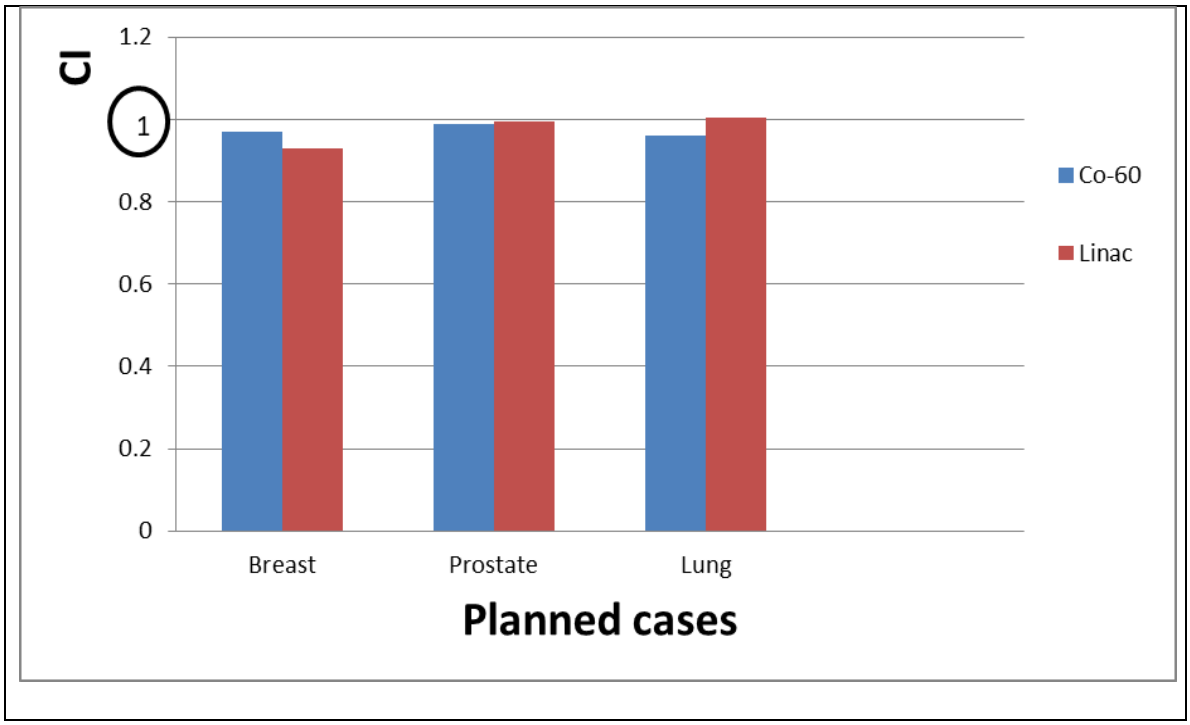


Figure 4.7: Conformity index between cobalt-60-based and linac-based treatment plans for selected cases

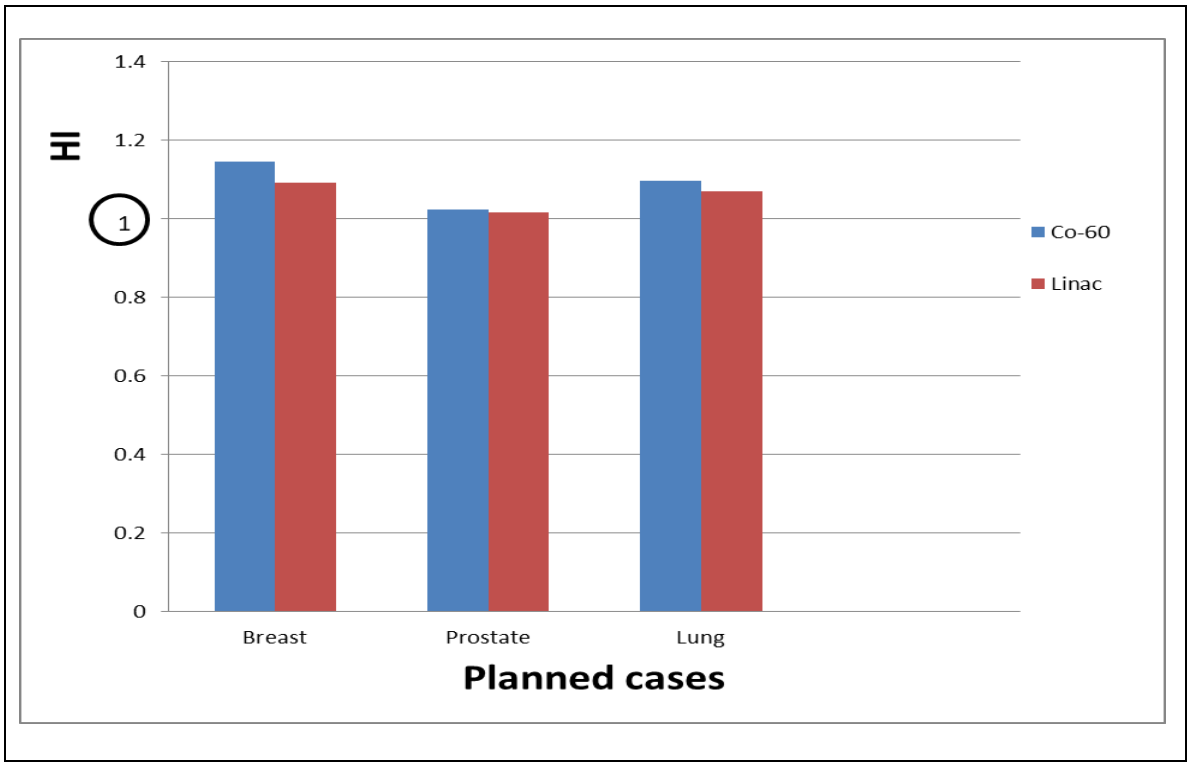


Figure 4.8: Homogeneity index between cobalt-60-based and linac-based treatment plans for the selected cases**.**

The value of CI equal to 1.0005 for lung plan was superior and close to ideal RTOG value of 1 followed by prostate plan with the value 0.9948 both generated by linac treatment planning system. However, cobalt-60-based plan generated a superior conformal plan with CI equal to 0.9705 for the breast case. Dose homogeneity for all selected plans was superior for linac-based plans than cobalt-60 based plans.

The graphs in Figure 4.7 and Figure 4.8 have shown that CI and HI for prostate plan were much comparable for both cobalt-60 based plan and linac-based plan. Furthermore, for all the three selected cases the PTV conformity and homogeneity indices were not only relatively close to the ideal RTOG value of 1 but also within the acceptable range of RTOG protocol.

4.3 Machine output and verification of treatment plans

The results of end-to-end test from a PMMA slab phantom with Farmer type ionization chamber positioned at 5cm and prescribed dose of 2.00 Gy/fraction show relative variation between the calculated and measured doses for the two treatment machines. The deviations of 1.5% and 0.83% with a tolerance of $\pm 2\%$ between cobalt-60 machine and linac respectively were recorded.

Similarly, verification of planned and delivered dose in anthropomorphic phantom show a deviation of 0.5% and 0% with a tolerance of $\pm 1\%$ between cobalt-60-based plan and linac-based plan respectively. Hence, both machines were performing according to the calibrated dataset within the tolerance level.

4.4 Discussion

The primary objective of this study was to ascertain if cobalt-60 machine could be feasible to generate and deliver treatment plans with optimal treatment indices comparable to those of a linear accelerator for selected cancer cases due to factors such as nature of the tumor (surface or deep seated cancer), tissue inhomogeneities (bone, soft and air interaction of the beam), algorithms used, beam modifiers (wedges/MLCs) as well as energy differences. As such treatment plans were generated with cobalt-60 and linear accelerator-base conformal radiotherapy and thereafter evaluation and comparison of treatment (dosimetric) parameters and indices was conducted.

ICRU 62 and RTOG introduced as well as defined conformity index (CI) and homogeneity index (HI). The main purposes for these indices are to assist in necessary decision making process in radiotherapy since DVH alone is insufficient [8, 13].

Therefore, Petrova et al. (2017) and other studies such as that of Vaezzadel et al. (2012), Caraman et al. (2016), Yu et al. (2013), Helal and Omar (2015) have concluded that conformity index and homogeneity index are two important analysis tools of treatment plans during conformal radiotherapy [9, 21, 17, 51, 15].

This study has established that with an accurate and careful selection of beam arrangement even with cobalt-60 machine, it is possible to improve target dose conformity and dose homogeneity. The prostate and breast cases have proved cobalt-60-based plans to have conformity indices comparable to that of linac with breast CI-value of 0.9705 compared to 0.9303 of linac-based plan. This may be attributed to the thickness of the breast tissue and the fact that the PTV is closer to the skin. The results for breast plan in this study are in tandem with Adams and Warrington's (2008) findings which observed that cobalt-60 offers a suitable alternative to 6 MeV linac for the treatment of breast cancer [20]. However, the increased dose to OAR such as lung for breast irradiation with cobalt-60 machine was due to the larger penumbra for telecobalt beams.

In particular, the study has shown that the conformal coverage of PTV and dose homogeneity distribution for prostate case was found to be more comparable between cobalt-60-based plan and linear accelerator- based plan. Apart from that, doses to OARs even though slightly higher for cobalt-60-based plans were within the acceptance criteria referred in QUANTEC. This illustrates the possibility of cobalt-60 to treat deep-seated tumors for which some studies have previously cited to be unsuitable for low energy beams [20, 24, 52].

For lung plans the conformity indices and homogeneity indices were slightly different from each other with linac-based plan having superior conformal coverage of the PTV and uniform dose distribution. However, for both plans the indices were significantly within the range of RTOG protocol. This suggests the limitation of cobalt-60 machine having conformal and homogeneous dose distribution for in-homogeneous organs such as lung. That is the reason why studies have called for modernization of cobalt units with state of the art ancillary devices so that it could be fully acceptable for the treatment of various cancers [20, 22, 24, 52].

In agreement with observation by Aoyama et.al (2006) and Vaezzadel et al. (2012), the result of this study shows that high energy beam from linear accelerator delivered minimal doses to organ at risks and normal structures than lower energy beam from cobalt-60 machine [53, 21]. It has also been observed that for cobalt-60 prostate plan, increasing the number of beams from 4-fields to 5-fields decreased the dose to organ at risks. This is in line with Vaezzadel et al. (2012) claim that "by increasing the number of beams, one can compensate for the low energy defect" [21]. On high doses to femur heads observed in this study, it is because of two lateral fields passing through the femoral heads which can be reduced by using low lateral weighted beams.

Radiotherapy machines are calibrated to deliver a known dose under standard conditions. As such, evaluation of machine output for cobalt-60 machine and linac has shown that both machines were performing according to the calibrated dataset within the tolerance levels. Therefore, the study has shown that both treatment machines are able to deliver doses as planned which assures consistence and accurate dose delivery to the patients.

A limitation of this study is that the investigation was performed with only two machines available and for small number of selected cancer cases. Increasing the number of machines and covering almost all sites would help to make the results of conformal index and homogeneity index valid to all telecobalt-based plans and linac-based plans. However, various studies have already investigated the CI and HI only for linac-based plans for different treatment techniques, algorithms used and treatment sites.

The other limitation is that the quality of every treatment plan is subjective/dependent on the oncologist main priority and the experience of the planning physicist. If the oncologist main aim is curative, then the plan will be more conformal and with homogeneous dose distribution but having higher doses to normal tissues. Also, the more experienced the physicist is with the treatment planning system (TPS), the more conformal and homogeneous the dose plans produced.

Finally, the plan delivery also affects the quality of treatment. Quality control of treatment planning machine is then conducted weekly, monthly and annually to make sure that plan delivery matches the quality of plan produced.

Chapter Five

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

Cobalt-60-based treatment plans for the selected three dimensional conformal radiotherapy (3D-CRT) cases of breast, prostate and lung offer conformal and homogeneous dose distribution more comparable to that of linac-based treatment plans. If well maintained with recommended daily, weekly, and monthly as well as annual QC's, the machine output performance in terms of consistence and accurate dose between the planned and delivered is highly achieved. For any decision on the choice of teletherapy machine, local needs, conditions and resources will have to be factored in with the primary goal being the sustainability of the radiotherapy service over the useful lifetime of the equipment.

Therefore, in situations where there are major challenges of inadequate financial capacity and maintenance associated with linear accelerators, the use of telecobalt (Cobalt-60) machines should be encouraged until financial and sustainability of linear accelerator machine is guaranteed for the benefit of patients.

5.2 RECOMMENDATIONS

The study recommends the following;

5.2.1 Medical Physicists and Oncology Staff

i. The physicists should maintain an open dialogue with the clinicians and related staff members on limitation of the treatment machines and treatment planning systems in terms of dose conformity and dose homogeneity. This will facilitate improvement and purchase of new treatment machines and equipment in radiotherapy for quality health care of patients.

ii. Medical physicists and oncology staff should participate in international radiotherapy plan competitions (e.g Radiation Knowledge) in order to improve quality performance of individual planners as well as the quality of plans generated for radiotherapy cancer patients.

5.2.2 Vendors and International radiotherapy Agencies

i. Should sensitize, empower and assist member states and multiple partners worldwide to build capacity in modern radiotherapy services at national level. This will help developing countries to provide quality cancer treatment and care.

ii. The vendors of radiotherapy machines should consider developing a linear accelerator that will be more likely to withstand damage to electronic parts from fluctuations in electricity power supply and all climate conditions in developing countries such as the continent of Africa.

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Appendix A: Summary of QUANTEC

Table 1. QUANTEC Summary: Approximate Dose/Volume/Outcome Data for Several Organs Following Conventional Fractionation (Unless Otherwise Noted)*

Organ	Volume segmented	Irradiation type (partial organ unless otherwise stated)†	Endpoint	Dose (Gy), or dose/volume parameters†	Rate (%)	Notes on dose/volume parameters
Brain	Whole organ	3D-CRT	Symptomatic necrosis	Dmax <60	<3	Data at 72 and 90 Gy, extrapolated from BED models
	Whole organ	3D-CRT	Symptomatic necrosis	Dmax = 72	5	
	Whole organ	3D-CRT	Symptomatic necrosis	Dmax = 90	10	
	Whole organ	SRS (single fraction)	Symptomatic necrosis	V12 <5–10 cc	<20	Rapid rise when V12 > 5–10 cc
Brain stem	Whole organ	Whole organ	Permanent cranial neuropathy or necrosis	Dmax <54	<5	
	Whole organ	3D-CRT	Permanent cranial neuropathy or necrosis	D1–10 cc‖ ≤59	<5	
	Whole organ	3D-CRT	Permanent cranial neuropathy or necrosis	Dmax <64	<5	Point dose <<1 cc
	Whole organ	SRS (single fraction)	Permanent cranial neuropathy or necrosis	Dmax <12.5	<5	For patients with acoustic tumors
Optic nerve / chiasm	Whole organ	3D-CRT	Optic neuropathy	Dmax <55	<3	Given the small size, 3D CRT is often whole organ‡‡
	Whole organ	3D-CRT	Optic neuropathy	Dmax 55–60	3–7	
	Whole organ	3D-CRT	Optic neuropathy	Dmax >60	>7-20	
	Whole organ	SRS (single fraction)	Optic neuropathy	Dmax <12	<10	
Spinal cord	Partial organ	3D-CRT	Myelopathy	Dmax = 50	0.2	Including full cord cross-section
	Partial organ	3D-CRT	Myelopathy	Dmax = 60	6	
	Partial organ	3D-CRT	Myelopathy	Dmax = 69	50	
	Partial organ	SRS (single fraction)	Myelopathy	Dmax = 13	1	Partial cord cross-section irradiated
	Partial organ	SRS (hypofraction)	Myelopathy	Dmax = 20	1	3 fractions, partial cord cross-section irradiated
Cochlea	Whole organ	3D-CRT	Sensory neural hearing loss	Mean dose ≤45	<30	Mean dose to cochlear, hearing at 4 kHz
	Whole organ	SRS (single fraction)	Sensory neural hearing loss	Prescription dose ≤14	<25	Serviceable hearing
Parotid	Bilateral whole parotid glands	3D-CRT	Long term parotid salivary function reduced to <25% of pre-RT level	Mean dose <25	<20	For combined parotid glands¶
	Unilateral whole parotid gland	3D-CRT	Long term parotid salivary function reduced to <25% of pre-RT level	Mean dose <20	<20	For single parotid gland. At least one parotid gland spared to <20 Gy¶

(*Continued*)

Table 1. QUANTEC Summary: Approximate Dose/Volume/Outcome Data for Several Organs Following Conventional Fractionation (Unless Otherwise Noted)* (*Continued*)

Organ	Volume segmented	Irradiation type (partial organ unless otherwise stated)†	Endpoint	Dose (Gy), or dose/volume parameters†	Rate (%)	Notes on dose/volume parameters
	Bilateral whole parotid glands	3D-CRT	Long term parotid salivary function reduced to <25% of pre-RT level	Mean dose <39	<50	For combined parotid glands (per Fig. 3 in paper) ¶
Pharynx	Pharyngeal constrictors	Whole organ	Symptomatic dysphagia and aspiration	Mean dose <50	<20	Based on Section B4 in paper
Larynx	Whole organ	3D-CRT	Vocal dysfunction	Dmax <66	<20	With chemotherapy, based on single study (see Section A4.2 in paper)
	Whole organ	3D-CRT	Aspiration	Mean dose <50	<30	With chemotherapy, based on single study (see Fig. 1 in paper)
	Whole organ	3D-CRT	Edema	Mean dose <44	<20	Without chemotherapy, based on single study in patients without larynx cancer**
	Whole organ	3D-CRT	Edema	V50 <27%	<20	
Lung	Whole organ	3D-CRT	Symptomatic pneumonitis	V20 ≤ 30%	<20	For combined lung. Gradual dose response
	Whole organ	3D-CRT	Symptomatic pneumonitis	Mean dose = 7	5	Excludes purposeful whole lung irradiation
	Whole organ	3D-CRT	Symptomatic pneumonitis	Mean dose = 13	10	
	Whole organ	3D-CRT	Symptomatic pneumonitis	Mean dose = 20	20	
	Whole organ	3D-CRT	Symptomatic pneumonitis	Mean dose = 24	30	
	Whole organ	3D-CRT	Symptomatic pneumonitis	Mean dose = 27	40	
Esophagus	Whole organ	3D-CRT	Grade ≥3 acute esophagitis	Mean dose <34	5–20	Based on RTOG and several studies
	Whole organ	3D-CRT	Grade ≥2 acute esophagitis	V35 <50%	<30	A variety of alternate threshold doses have been implicated. Appears to be a dose/volume response
	Whole organ	3D-CRT	Grade ≥2 acute esophagitis	V50 <40%	<30	
	Whole organ	3D-CRT	Grade ≥2 acute esophagitis	V70 <20%	<30	
Heart	Pericardium	3D-CRT	Pericarditis	Mean dose <26	<15	Based on single study
	Pericardium	3D-CRT	Pericarditis	V30 <46%	<15	
	Whole organ	3D-CRT	Long-term cardiac mortality	V25 <10%	<1	Overly safe risk estimate based on model predictions

(*Continued*)

Table 1. QUANTEC Summary: Approximate Dose/Volume/Outcome Data for Several Organs Following Conventional Fractionation (Unless Otherwise Noted)* (*Continued*)

Organ	Volume segmented	Irradiation type (partial organ unless otherwise stated)†	Endpoint	Dose (Gy), or dose/volume parameters†	Rate (%)	Notes on dose/volume parameters
Liver	Whole liver – GTV	3D-CRT or Whole organ	Classic RILD††	Mean dose <30-32	<5	Excluding patients with pre-existing liver disease or hepatocellular carcinoma, as tolerance doses are lower in these patients
	Whole liver – GTV	3D-CRT	Classic RILD	Mean dose <42	<50	
	Whole liver – GTV	3D-CRT or Whole organ	Classic RILD	Mean dose <28	<5	In patients with Child-Pugh A preexisting liver disease or hepatocellular carcinoma, excluding hepatitis B reactivation as an endpoint
	Whole liver – GTV	3D-CRT	Classic RILD	Mean dose <36	<50	
	Whole liver –GTV	SBRT (hypofraction)	Classic RILD	Mean dose <13 <18	<5 <5	3 fractions, for primary liver cancer 6 fractions, for primary liver cancer
	Whole liver – GTV	SBRT (hypofraction)	Classic RILD	Mean dose <15 <20	<5 <5	3 fractions, for liver metastases 6 fractions, for liver metastases
	>700 cc of normal liver	SBRT (hypofraction)	Classic RILD	D_{max} <15	<5	Critical volume based, in 3–5 fractions
Kidney	Bilateral whole kidney‡	Bilateral whole organ or 3D-CRT	Clinically relevant renal dysfunction	Mean dose <15–18	<5	
	Bilateral whole kidney‡	Bilateral whole organ	Clinically relevant renal dysfunction	Mean dose <28	<50	
	Bilateral whole kidney‡	3D-CRT	Clinically relevant renal dysfuntction	V12 <55% V20 <32% V23 <30% V28 <20%	<5	For combined kidney
Stomach	Whole organ	Whole organ	Ulceration	D100‖ <45	<7	
Small bowel	Individual small bowel loops	3D-CRT	Grade ≥ 3 acute toxicity§	V15 <120 cc	<10	Volume based on segmentation of the individual loops of bowel, not the entire potential peritoneal space
	Entire potential space within peritoneal cavity	3D-CRT	Grade ≥ 3 acute toxicity§	V45 <195 cc	<10	Volume based on the entire potential space within the peritoneal cavity

(*Continued*)

Table 1. QUANTEC Summary: Approximate Dose/Volume/Outcome Data for Several Organs Following Conventional Fractionation (Unless Otherwise Noted)* (*Continued*)

Organ	Volume segmented	Irradiation type (partial organ unless otherwise stated)†	Endpoint	Dose (Gy), or dose/volume parameters†	Rate (%)	Notes on dose/volume parameters
Rectum	Whole organ	3D-CRT	Grade ≥ 2 late rectal toxicity, Grade ≥ 3 late rectal toxicity	V50 <50%	<15 <10	Prostate cancer treatment
	Whole organ	3D-CRT	Grade ≥ 2 late rectal toxicity, Grade ≥ 3 late rectal toxicity	V60 <35%	<15 <10	
	Whole organ	3D-CRT	Grade ≥ 2 late rectal toxicity, Grade ≥ 3 late rectal toxicity	V65 <25%	<15 <10	
	Whole organ	3D-CRT	Grade ≥ 2 late rectal toxicity, Grade ≥ 3 late rectal toxicity	V70 <20%	<15 <10	
	Whole organ	3D-CRT	Grade ≥ 2 late rectal toxicity, Grade ≥ 3 late rectal toxicity	V75 <15%	<15 <10	
Bladder	Whole organ	3D-CRT	Grade ≥ 3 late RTOG	Dmax <65	<6	Bladder cancer treatment. Variations in bladder size/shape/location during RT hamper ability to generate accurate data
	Whole organ	3D-CRT	Grade ≥3 late RTOG	V65 ≤50 % V70 ≤35 % V75 ≤25 % V80 ≤15 %		Prostate cancer treatment Based on current RTOG 0415 recommendation
Penile bulb	Whole organ	3D-CRT	Severe erectile dysfunction	Mean dose to 95% of gland <50	<35	
	Whole organ	3D-CRT	Severe erectile dysfunction	D90‖ <50	<35	
	Whole organ	3D-CRT	Severe erectile dysfunction	D60-70 <70	<55	

Abbreviations: 3D-CRT = 3-dimensional conformal radiotherapy, SRS = stereotactic radiosurgery, BED = Biologically effective dose, SBRT = stereotactic body radiotherapy, RILD = radiation-induced liver disease, RTOG = Radiation Therapy Oncology Group.

* All data are estimated from the literature summarized in the QUANTEC reviews unless otherwise noted. Clinically, these data should be applied with caution. Clinicians are strongly advised to use the individual QUANTEC articles to check the applicability of these limits to the clinical situation at hand. They largely do not reflect modern IMRT.

† All at standard fractionation (*i.e.*, 1.8–2.0 Gy per daily fraction) unless otherwise noted. Vx is the volume of the organ receiving ≥ x Gy. Dmax = Maximum radiation dose.

‡ Non-TBI.

§ With combined chemotherapy.

‖ Dx = minimum dose received by the "hottest" x% (or x cc's) of the organ.

¶ Severe xerostomia is related to additional factors including the doses to the submandibular glands.

** Estimated by Dr. Eisbruch.

†† Classic Radiation induced liver disease (RILD) involves anicteric hepatomegaly and ascites, typically occurring between 2 weeks and 3 months after therapy. Classic RILD also involves elevated alkaline phosphatase (more than twice the upper limit of normal or baseline value).

‡‡ For optic nerve, the cases of neuropathy in the 55 to 60 Gy range received ≈ 59 Gy (see optic nerve paper for details). Excludes patients with pituitary tumors where the tolerance may be reduced.