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DOSIMETRIC COMPARISON OF BREAST IRRADIATION TECHNIQUES

BY

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DECLARATION

This thesis is the result of research work carried out by Prosper Amankwah in the Department of Medical Physics, School of Nuclear and Allied Sciences, University of Ghana, under the supervision of Dr. Samuel Nii Adu Tagoe and Dr. Mark Pokoo-Aikins.

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ABSTRACT

This study aims to evaluate and compare the dosimetric performance of four advanced radiotherapy techniques: volumetric modulated arc therapy (VMAT), intensity modulated radiotherapy (IMRT), and two hybrid techniques (3-D conformal radiotherapy (3D-CRT) combined with 2 or 5 IMRT beams) in the treatment of breast cancer. The focus is on achieving optimal target coverage while minimising radiation exposure to organs at risk (OARs), including the heart, lungs, and contralateral breast, for both chest wall and intact breast irradiation scenarios. Four treatment plans were developed for each patient using the Varian Eclipse treatment planning system (v18.0), with a prescribed dose of 50 Gy in 25 fractions. Dosimetric comparisons were made to assess the homogeneity index (HI), conformity index (CI), and dose to OARs. Dose-volume histograms (DVHs) were used to assess the doses received by OARs, in line with RTOG-1305 and ICRU Report 83 guidelines. Monitor units (MU's) and estimated delivery times were also recorded to evaluate the complexities associated with each technique. Key findings indicate that while VMAT achieved the best dose conformity, as evidenced by the lowest conformity index (CI) values of 1.063 ± 0.034 for chestwall and 1.018 ± 0.036 for intact brerast, the Hybrid (5 IMRT beams) technique offered superior dose homogeneity across both treatment scenarios (0.071 ± 0.017 for chestwall and 0.065 ± 0.011 for intact breast). Furthermore, the Hybrid (2IMRT beams) approach was notable for its ability to spare critical organs, particularly the contralateral breast, heart, and lungs. Treatment times varied among the techniques, with Hybrid (2 IMRT Beams) being the technique with the fewest monitor units for chest wall cases (729.0 ± 80.7) and VMAT having the fewest MU for intact breast cases (410.1 ± 53.6), while IMRT was found to be the technique with the most monitor units (MU) in both scenarios. This research underscores the need for tailored radiotherapy planning that considers individual patient factors, clinical risks, and stringent patient-specific quality assurance (PSQA) practices to ensure accurate dose delivery.

DEDICATION

This research work is dedicated to my parents, Elder Aboagye Amankwah and Madam Helena Benful.

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LIST OF ABBREVIATIONS

3D-CRT: Three-dimensional conformal radiation therapy

AAA: Analytical Anisotropic Algorithm

ALND: Axillary Lymph Node Dissection

ANOVA: Analysis of Variance

APBI: Accelerated Partial Breast Irradiation

ASTRO: American Society for Radiation Oncology.

CI: Conformity Index

CT: Computed Tomography

CTV: Clinical Target Volume

DICOM: Digital Imaging and Communication in Medicine

DR: Dose Rate

DVH: Dose Volume Histogram

EBRT: External Beam Radiation Therapy

ER: Oestrogen Receptors

ESTRO: European Society for Radiotherapy and Oncology

FIF: Field-in-Field

GTV: Gross Tumour Volume

HDR: High Dose Rate

HER2: Human Epidermal Growth Factor Receptor 2

HF-WBRT: Hypo-Fractionated-Whole Breast Radiation Therapy

HI: Homogeneity Index

IAEA: International Atomic Energy Agency

ICRU: International Commission on Radiological Units and Measurements

IGRT: Image Guided Radiation Therapy

IMRT: Intensity Modulated Radiation Therapy

IORT: Intraoperative Radiotherapy

MCS: Modulation Complexity Score

MLC: Multi-Leaf Collimator

MRgRT: Magnetic Resonance-Guided Radiation Therapy

MRI: Magnetic Resonance Imaging

MU: Monitor Units

NTCP: Normal Tissue Complication Probability

OARs: Organs at Risk

PET: Positron Emission Tomography

PR: Progesterone Receptors

PSQA: Patient-Specific Quality Assurance

PTV: Planning Target Volume

RTOG: Radiation Oncology Task Group

SLNB: Sentinel Lymph Node Biopsy

SPECT: Single Positron Emission Computed Tomography

TCP: Tumour Control Probability

TPS: treatment Planning System

VMAT: Volumetric Arc Therapy

WBRT: Whole Breast Radiation Therapy

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND

Breast cancer is defined as a malignancy that develops within the tissues of the breast, encompassing both the ducts and lobules. According to recent data from the Global Cancer Statistics, breast cancer is identified as the predominant cancer in females worldwide, as it accounts for 1 of every 9 cancer diagnoses which is 11.6% of all cancer diagnoses in the world (Bray *et al*., 2024). In 2022, there were 2.3 million new breast cancer cases diagnosed of which 665,684 died from the disease (Bray *et al*., 2024). It stands as the primary leading cause of cancer-related deaths in developing regions and the secondary course in developed regions. The implementation of breast cancer screening programmes has helped to advance the detection of breast cancer, which has led to improved treatment outcomes (Ginsburg *et al*., 2020). For individuals diagnosed with early-stage breast cancer, a conservative management approach involving breast-conserving surgery is favoured over the radical mastectomy commonly employed for late-stage cases (Dahlui *et al*., 2023).

Breast cancer treatments often involve a combination of surgery, chemotherapy, radiation therapy, hormone therapy, and targeted therapy. After surgery, adjuvant therapy is commonly recommended to reduce the risk of local and regional recurrences. Radiotherapy plays a crucial role in this regard by utilising advanced treatment planning techniques to enhance the targeting of cancerous issues while minimising exposure to healthy tissues (Bi *et al*., 2022). Advanced treatment planning techniques such as 3-dimensional conformal radiation therapy (3D-CRT), intensity modulated radiation therapy (IMRT), and volumetric arc therapy (VMAT) are now widely used in the treatment of breast cancer. 3D-CRT, employing two opposed, wedge and tangential fields, has historically been the standard approach for breast cancer eradication (Bi *et al*., 2022). This technique utilises multi-leaf collimators (MLC) to shield nearby healthy

tissues (such as the ipsilateral lung, contralateral lung, contralateral breasts and heart). While 3D-CRT simplifies planning, treatment delivery, and enhances local control, concerns remain about potential toxicities to organs at risk (OARs) due to radiation exposure, prompting the development and adoption of more precise and targeted techniques like VMAT and IMRT (Bi *et al*., 2021). The FIF technique is a forward planning intensity-modulated technique (Nakamura *et al*., 2011) in which fields are created by strategically placing multi-leaf collimator (MLC) leaves in hotspots. In this method, hotspots and cold spots are reduced. In the FIF technique, treatments are carefully designed to achieve a uniform dose distribution while effectively sparing normal tissues, which are key advantages of this approach (Nakamura *et al*., 2011; Takabi *et al*., 2023).

IMRT delivers a non-uniform fluence to optimise the dose distribution by dividing each treatment beam into smaller segments. These small beam segments yield high breast dose coverage and provide an improved conformity index (CI) (Bi *et al*., 2022). VMAT, on the other hand, involves gantry rotation and continuous radiation beam delivery, adjusting both the dose rates (DR) and the configuration of MLCs concurrently to achieve precise and conformal dose distribution. IMRT and VMAT are noted for their significant advantages in achieving uniform dose distribution and coverage. However, IMRT may be more prone to set-up errors and changes in breast shape, especially in whole breast radiotherapy (Bi *et al*., 2022).

To enhance the PTV and OAR symmetry, a more recent alternative to 3D conventional, IMRT or VMAT treatment is the hybrid approach, which combines two techniques to create a more optimised dosimetric outcome and was proposed by Nakamura *et al. (2014*). The method comprised two opposed tangential open beams and two inverse-planned IMRT beams. The open beams contribute a greater percentage of the prescribed dose, while the IMRT beams contribute the remaining percentage. Nakamura *et al*. proved that the hybrid IMRT had

excellent performance in target quality and offset the geometric uncertainties for patients who underwent whole breast RT using the hybrid technique (Nakamura *et al*., 2014).

1.2 PROBLEM STATEMENT

In radiotherapy for breast cancer, different planning techniques can greatly impact how effective the treatment is and how safe it is for the patient. Traditional 3D conformal radiation therapy (3D-CRT) has limitations, particularly in how well it targets the tumour while protecting the nearby healthy tissues. As a result, patients often face side effects like skin changes, lymphoedema, lung inflammation, and breast pain (Smith *et at., 2018)*.

To reduce these side effects, newer techniques like intensity modulated radiation therapy (IMRT), volumetric arc therapy (VMAT), and hybrid techniques (which combine 3D-CRT and IMRT) have been developed. These methods have improved how the radiation dose is delivered and have better-protected organs at risk (OARs), like the heart and lungs. However, there are still challenges in achieving the best dose balance, ensuring that the tumour receives enough radiation while minimising damage to healthy tissues. This is especially important for left-sided breast cancer, where the heart is more at risk.

Additionally, there remains a lack of comprehensive comparative studies that assess the dosimetric performance and potential clinical implications of these techniques across different clinical scenarios. This gap in the literature hinders the development of evidence-based guidelines for selecting the most appropriate planning strategy in breast cancer radiotherapy. This study aims to compare different advanced radiotherapy planning technique for breast cancer. The objective is to identify methods that offer superior target coverage, improved homogeneity, and enhanced protection of OARs, ultimately contributing to safer, more effective treatment delivery and improved patient outcomes.

1.3 RELEVANCE AND JUSTIFICATION

The optimisation of radiotherapy techniques is crucial for enhancing treatment efficacy and minimising side effects in breast cancer patients, although clinical outcomes cannot be determined directly in this research. However, by comparing the dosimetric outcomes of different techniques, this research will enhance the understanding of how advanced radiotherapy methods can be optimised for better tumour targeting and OAR sparing and will demystify the risk associated with these techniques. The findings will also provide evidence-based recommendations for clinicians, contributing to more informed choices in radiotherapy technique selection. The study will add to the existing body of knowledge on breast irradiation techniques, supporting future research and clinical advancements.

1.4 AIMS AND OBJECTIVES

The main objective of this study is to evaluate the superiority of the various irradiation techniques for breasts during external beam radiotherapy.

Specific Objectives include:

1. To assess the quality of treatment plants among various techniques to evaluate their potential benefits in terms of target coverage and dose homogeneity.
2. To assess the toxicity of Organs at Risk associated with each technique using the Radiotherapy Oncology Group constraints.
3. To identify the optimal technique suitable for chest wall and intact breast irradiation.
4. To evaluate the estimated delivery times for each technique.

1.5 SCOPE AND DELIMITATION

This study is focused on the comparative analysis of advanced radiotherapy planning techniques specifically for breast cancer irradiation. The study includes a detailed evaluation of intensity-modulated radiation therapy (IMRT), volumetric arc therapy (VMAT) and hybrid, an option that combines 3D-CRT with IMRT. The research will primarily assess dosimetric parameters such as target coverage, dose homogeneity, conformity index, organs at risk (OARs) sparing, and treatment delivery time.

This study will be limited to CT images of breast cancer patients on the treatment planning system. Treatment plans for these advanced techniques will be generated and compared. Clinical outcomes such as survival rates, recurrence, and long-term toxicities are beyond the scope of this study and will not be evaluated. The research will also not cover other radiotherapy techniques or modalities that are not directly related to breast cancer irradiation, nor will it address variations in patient demographics, tumour biology or genetic factors that may influence treatment outcomes. The scope is further delimited by focusing on cases involving whole breasts and chest wall irradiation, excluding supraclavicular or nodal involvement and other site-specific breast cancer treatments.

1.6 ORGANISATION OF THESIS

This thesis is organised into five chapters; Chapter one provides an introduction to the study, including the background, problem statement, relevance, aims, objectives, scope, and delimitation. It sets the stage for the research by outlining the key concepts and issues to be addressed. Chapter two presents a comprehensive review of the existing literature relevant to the study. It covers breast cancer epidemiology, different treatment modalities for breast

cancer, the evolution of radiotherapy techniques, recent advancements, and previous comparative studies on dosimetric outcomes in breast cancer irradiation.

Chapter three describes the methodology employed in this research. It details the steady design, patient selection criteria, data collection methods, treatment planning processes, and the criteria for dosimetric evaluation.

Chapter four focuses on the results and analysis. This chapter presents the comparative dosimetric data for the different radiotherapy techniques, discusses the findings in relation to the study objectives, and highlights any significant trends or patterns observed.

Chapter five provides the conclusion and recommendations. It summarises the key findings of the study, discusses their implications for clinical practice, and suggests areas for future research. The chapter also offers evidence-based recommendations for the optimal use of radiotherapy planning techniques in breast cancer treatment.

References appendices and any supplementary materials follow the main chapters providing additional support and documentation for the research conducted.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 OVERVIEW OF BREAST CANCER EPIDEMIOLOGY

Cancer arises from a series of molecular alterations that impair cells' normal functions. These alterations disable the usual regulatory systems that prevent excessive cell growth and invasion into other healthy tissues, leading to the uncontrolled behavioural characteristic of cancer cells. In other words, cancer occurs when the regulatory mechanisms that typically restrain cell proliferation and prevent tissue invasion malfunction (Angahar, 2017). It is a major global health concern, as it affects millions and different categories of people resulting in significant morbidity and mortality. Cancers can arise in any part of the body, including the breast, lung, colon, prostate, skin, head and neck as a result of genetic mutations. These mutations, either inherited or acquired throughout a person's lifetime, are as a result of a variety of circumstances, including ageing, lifestyle choices, and exposure to carcinogens that disrupt normal cell growth and division (Parsa, 2012).

Among the numerous types of cancers, breast cancer stands out as the second most prevalent and impactful form of the disease. According to recent data from the Global Cancer Statistics, breast cancer is identified as the predominant cancer in females worldwide, as it accounts for 1 of every 9 cancer diagnoses, which is 11.6% of all cancer site diagnosis in the world. In 2022, there were 2.3 million new breast cancer cases diagnosed, of which 665,684 of died from the disease (Bray *et al*., 2024). Breast cancer affects both genders, although it is relatively rare in men. In 140 out of 180 countries, it stands as the primary cause of mortality among women (Angahar, 2017).

Breast cancer is a malignant tumour that originates in breast tissue. This disease encompasses various forms, as it can manifest in different regions of the breast, including the ducts, lobules, or the interstitial tissue (Feng *et al*., 2018). The type of breast cancer is identified by the

particular cells that are impacted. Breast malignancies are generally categorised as either carcinomas or sarcomas, based on the cell of origin.

Breast tumours classified as carcinomas develop from the epithelial cells lining the terminal ducts and lobules, which are responsible for milk production. In contrast, sarcomas are a very rare form of breast cancer (less than 1% of all cases of primary breast cancer) that arise from the stromal cells, which include blood vessel and myofibroblast cells. These two categories help in understanding the origin of the tumours. However, they are not always comprehensive, as some breast tumours can contain a mix of different cell types, complicating diagnosis and treatment (Feng *et al*., 2018).

Most breast cancers are carcinomas. Within this broad category, various types of breast cancer are distinguished based on their degree of invasiveness relative to the primary tumour sites (Makki, 2015). Being able to differentiate between the numerous subtypes with accuracy is essential because each one has distinct therapeutic implications and prognoses. Common breast cancers can be divided into three primary categories based on their invasiveness and pathological characteristics: invasive, metastatic, and non-invasive (or in situ) breast cancers. (Feng *et al*., 2018). They can also be categorised according to the existence or lack of receptors that affect therapy choices, such as human epidermal growth factor receptor 2 (HER2), progesterone receptors (PR), and oestrogen receptors (ER). The pathophysiology of breast cancer involves complex interactions between genetic mutations, hormonal influences, and microenvironmental factors, leading to dysregulated cell proliferation, impaired apoptosis, and increased angiogenesis (Łukasiewicz *et al*., 2021).

Various risk factors come together to contribute to how breast cancers are developed. For instance, breast cancer occurs in women as high as a hundred-fold compared to men; therefore, being a woman is the primary risk factor for the disease. The majority of breast cancer cases

are detected in women over the age of 55 years, indicating that ageing invariably raises one's risk of developing breast cancer (Feng *et al*., 2018). Other documented risk factors include; family history of breast cancer, genetic mutations such as BRCA1 and BRCA2 that has been passed down to offsprings or inherited, hormonal factors (which include early menarche, late menopause, specific oral contraceptive use and lack of breast feeding), reproductive history (such as nulliparity and having a first child at an older age), lifestyle factors (like obesity and alcohol consumption), a previous history of breast cancer or any cancer and exposure to ionising radiation. All these are several known conditions that predispose one to breast cancer (De Silva *et al*., 2019).

Early, detection of breast cancer through screening programmes is essential for improving treatment outcomes and reducing mortality rates. Mammography, clinical breast examinations, and breast self-examinations are all examples of common screening techniques. Breast cancer diagnosis is established by using diagnostic techniques such as ultrasound, magnetic resonance imaging (MRI), and biopsy. These tests provide the histological subtype, grade, and hormone receptor status of the cancer (Ginsburg *et al*., 2020). All these tumour characteristics help to decide on the treatment modality as well as the sequence of treatment. Standard treatment modalities include surgery (lumpectomy, mastectomy), radiation therapy and systemic therapy (chemotherapy, hormonal therapy, targeted therapy, and immunotherapy) (Board, 2024). The stage of diagnosis of breast cancer and tumour biology has a significant impact on the prognosis and response to treatment. Early-stage breast cancers generally have a more favourable prognosis, while advanced-stage or metastatic disease carries a poorer prognosis (Bhushan *et al*., 2021).

Understanding breast cancer within the broader context of cancers in general allows the appreciation of the unique challenges and opportunities that it presents. By exploring the epidemiology, risk factors, screening methods, treatment advancements, and survivorship,

valuable insights into how to combat this disease effectively is observed (Wilkinson & Gathani, 2022).

2.2 BREAST CANCER MANAGEMENT

Breast cancer is a multifaceted disease that demands a comprehensive, multimodality, and personalised approach to treatment. As one of the most common cancers, it affects millions of people globally. Effective management strategies are vital for improving outcomes and quality of life of patients (Wilkinson & Gathani, 2022). Treatments for breast cancer include a wide range of procedures that range from radiation and surgery to systemic therapies like hormone therapy, chemotherapy, targeted therapy, and immunotherapy (Board, 2024).

The management of breast cancer is not a one-size-fits-all approach but rather a tailored strategy that considers the unique characteristics of the tumour, the patient's overall health, and individual preferences. Healthcare specialists from several disciplines operate closely together to create customised treatment programmes that maximise therapeutic efficacy while reducing side effect (Odeh & Al-Balas, 2024).

In recent years, advancements in molecular profiling, genomic testing, and targeted therapies have revolutionised the landscape of breast cancer management, allowing for more precise and individualised treatment strategies. Personalised medicine approaches enable clinicians to identify specific genetic mutations or biomarkers within the tumour that guides treatment decisions and predicts response to therapy (Subhan *et al*., 2023).

2.2.1 SURGICAL APPROACH

Surgery plays a central role in the management of breast cancer, serving as a localised treatment modality for many patients. The objectives of surgical intervention are twofold: to remove the tumour and to assess the extent of the disease and response to treatment aiding in staging and treatment planning (Conti *et al*., 2023). Several surgical procedures are utilised in the

management of breast cancer; each tailored to the individual characteristics of the tumour and the patient's preferences.

2.2.1.1 BREAST-CONSERVING SURGERY (LUMPECTOMY)

Breast-conserving surgery, also known as lumpectomy or partial mastectomy, involves removing the tumour and a portion of the surrounding healthy breast tissue. The objective of this method is to ensure complete removal of the tumour while protecting the breast. In this approach, the aim is to preserve the breast while achieving complete tumour excision (Jordan *et al*., 2022). A lumpectomy is followed by radiation therapy to the remaining breast tissue to reduce the risk of local recurrence. It is an attractive option for patients seeking breast preservation and is suitable for early-stage breast cancer with favourable tumour characteristics.

2.2.1.2 MASTECTOMY

The removal of the entire breast tissue surgically is termed as mastectomy and is indicated in cases where breast-conserving surgery is not feasible or appropriate (Czajka & Pfeifer, 2023). It may be recommended for large tumours, multifocal disease and in cases with skin involvement.

Mastectomy can be either total or radical, which is the complete removal of the breast or removing part of the affected part of the breast together with the involved lymph nodes. It could also be a skin-sparing mastectomy, which involves preserving the breast skin envelope for reconstruction (Czajka & Pfeifer, 2023).

2.2.1.3 SENTINEL LYMPH NODE BIOPSY (SLNB) AND AXILLARY LYMPH NODE DISSECTION (ALND)

Evaluation of the axillary lymph nodes is essential for staging and treatment planning in breast cancer. Sentinel lymph node biopsy (SLNB) is a minimally invasive procedure that identifies the first lymph nodes to which the tumour is likely to spread (Chatterjee *et al*., 2015). It allows for accurate nodal staging while minimising the risk of lymphoedema and other complications associated with axillary lymph node dissection (ALND). ALND involves the removal of multiple axillary lymph nodes and may be indicated in cases where SLNB demonstrates lymph node involvement or when additional nodal assessment is warranted (Orsaria *et al*., 2014).

2.2.1.4 BREAST RECONSTRUCTION

Breast reconstruction may be performed concurrently with mastectomy or as a delayed procedure following initial cancer treatment. It aims to restore the shape and symmetry of the breast, enhancing the physical and psychological well-being of breast cancer survivors. Reconstruction options include implant-based reconstruction, autologous tissue reconstruction (using the patient's own tissue), or a combination of both methods (Allen & Mehrara, 2021).

2.2.2 CHEMOTHERAPY

Chemotherapy is a systemic treatment modality that involves the administration of potent drugs that target rapidly dividing cancer cells throughout the body, aiming to shrink tumours, prevent their spread, and improve overall survival. It is an essential aspect of the treatment of breast cancer, especially when the illness has spread to adjacent lymph nodes and breast, or when there is a significant chance of recurrence (Nakamura & Maeda, 2023). It is commonly used in patients with early-stage breast cancer who have a high risk of recurrence based on tumour size, lymph node involvement, and other prognostic factors (Rampurwala *et al*., 2014). Some key aspects to consider regarding chemotherapy in breast cancer management include adjuvant

chemotherapy which is given in addition to primary treatment, like surgery, to eradicate any cancer cells that may still be present and lower the risk of recurrence.

Neoadjuvant chemotherapy on the other hand is administered before surgery to reduce tumour size, downstaging the disease, and making breast-conserving surgery feasible for patients initially deemed ineligible for breast conservation. It also helps to assess tumour response to treatment and guide further management decisions (Thompson & Moulder-Thompson, 2012). Targeted chemotherapy agents, such as HER2-targeted therapies (e.g. trastuzumab, pertuzumab) and CDK4/6 inhibitors (e.g. palbociclib, ribociclib) are increasingly being used in the management of specific subtypes of breast cancer either to inhibit tumour growth or to slow cancer cell proliferation (Ferrando-Díez *et al*., 2022).

2.2.3 RADIOTHERAPY

Radiotherapy is a critical component of breast cancer treatment and it contributes significantly to enhancing patient outcomes. Targeting and eliminating cancer cells with the least amount of damage to healthy tissue is one of radiotherapy's key benefits. This makes it a useful treatment option for breast cancer, especially when administered early (Chen & Kuo, 2017). Radiation therapy techniques for breast cancer treatment encompass intensity-modulated radiation therapy (IMRT), volumetric modulated arc therapy (VMAT), field-in-field (FIF), and three-dimensional conformal radiation therapy (3DCRT). IMRT allows precise delivery of high radiation doses to the tumour while minimising exposure to surrounding healthy tissue. This improves the precision and accuracy of cancer treatment, thereby lowering potential side effects by effectively targeting the tumour while sparing surrounding healthy tissue (Rehman *et al*., 2018). In addition to having a shorter treatment duration, VMAT also exposes the tumour to high radiation doses while protecting nearby healthy tissue.

However, it is linked to a frequent increase in low doses in healthy tissues adjacent to the target volumes (Voyant *et al*., 2024). The FIF approach uses a multi-leaf collimator in which the

leaves are positioned strategically in locations where the radiation to the breast is significantly higher than the prescribed amount, thus creating “hot spots”. The technique allows for better dose conformity to the target volume, resulting in improved tumour coverage. By utilising the subfields and beam modulation, dose heterogeneity within the target volume can be minimised, which can lead to a more uniform dose distribution (Lee *et al*., 2008).

For a long time, 3DCRT has been the conventional and widely available, cost-effective radiotherapy method. However, it is less precise and less accurate in targeting cancer cells compared to IMRT and VMAT. This leads to excessive and greater exposure of the surrounding healthy tissue (Voyant *et al*., 2024). It is important to note that both low and high radiation exposure might raise the chance of lung and heart damage. Moreover, as documented in the literature, young women in particular have an increased risk of developing a second malignancy in the contralateral breast (Okonogi *et al*., 2022). The consequences and doses administered to healthy mammary glands are noteworthy, although less severe. For patients with breast cancer who have undergone surgery, chemotherapy, and radiotherapy are frequently the final stages of active treatment if necessary.

The biological effects of radiation therapy leads to the death of cancer cells. Radiation therapy may be performed following surgery to inhibit the growth of any remaining cancer cells (Baskar *et al*., 2014). A group of radiation oncologists, medical physicists, and dosimetrists simulates the dose of radiation therapy in advance before treatment is delivered to the patient. The therapy is individual-based. The specific case of the patient, their body type and state of health, informs the therapy planning process. The radiation dose is sufficient to destroy a cancer cell while allowing healthy cells to regenerate in preparation for the subsequent dose (Godette *et al*., 2018). Radiotherapy could be internal or external with reference to the radiation source position.

2.2.3.1 INTERNAL BEAM RADIATION THERAPY (BRACHYTHERAPY)

Brachytherapy, commonly referred to as internal radiation therapy, delivers a high radiation dose to the target area while limiting exposure to nearby healthy tissues. This is achieved by the insertion of radioactive sources within or close to the tumour site (Skowronek, 2017). In the context of breast cancer treatment, brachytherapy offers a localised approach to irradiating the tumour bed following breast-conserving surgery, also known as lumpectomy or partial mastectomy (Hickey & Lehman, 2021).

There are two types of brachytherapy techniques used for breast irradiation: interstitial brachytherapy and intracavitary brachytherapy. Interstitial brachytherapy involves the insertion of radioactive sources directly into the breast tissue surrounding the tumour bed using catheters or applicators as illustrated in Figure 2.1, A and B. This technique allows for precise dose delivery to the target volume while sparing nearby critical structures, such as the skin and chest wall (Cozzi *et al*., 2022). Intracavitary brachytherapy, illustrated in Figure 2.2, A and B, on the other hand, utilises a balloon catheter or a specialised applicator placed within the lumpectomy cavity. Radioactive sources are then temporarily inserted into the balloon or applicator, delivering radiation directly to the tumour bed while minimising exposure to healthy tissues (Erven *et al*., 2008).

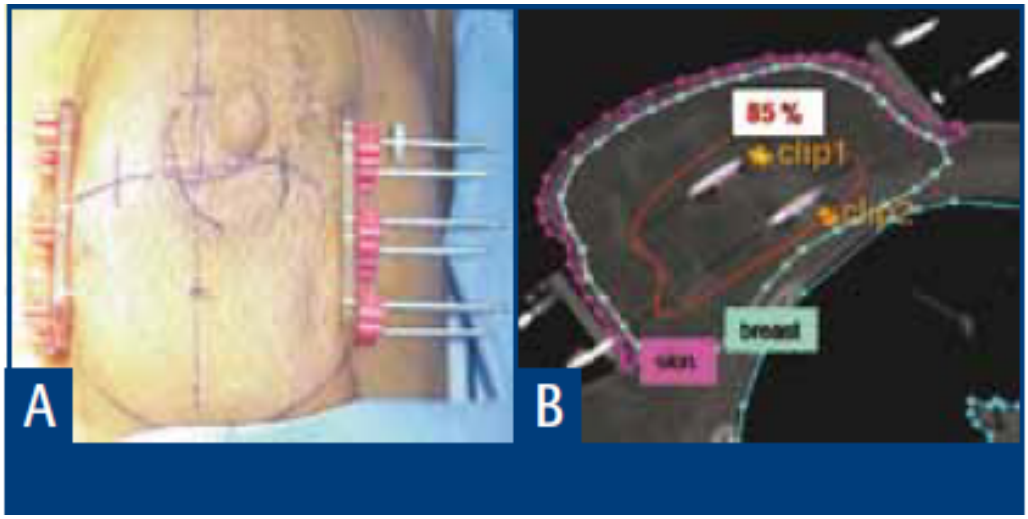

Figure 2.1 Multicatheter interstitial brachytherapy. A: External appearance of the implant. B: Transversal CT slice with an indication of the 85% isodose (—), at a large distance from the skin (Erven *et al*., 2008).

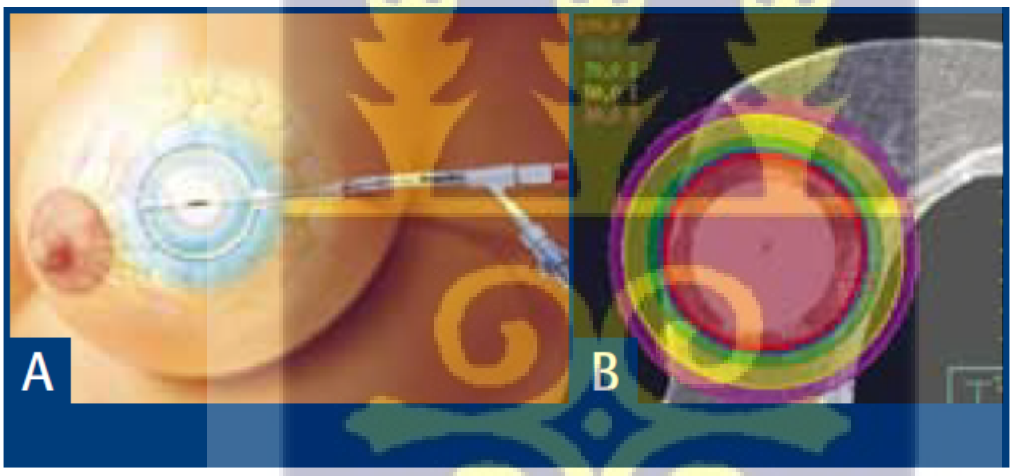

Figure 2.2 Intracavitary balloon brachytherapy. A: Presentation of the Mammosite® catheter. B: Transversal CT slice with an indication of the isodoses (view colour code). Note the 100% isodose reaching the skin (Erven *et al*., 2008).

Brachytherapy offers several advantages for breast cancer patients compared to traditional external beam radiation therapy (EBRT). It typically involves a shorter overall treatment duration, often completed in just a few days compared to several weeks with EBRT. This accelerated treatment schedule can improve patient convenience and compliance while

reducing the overall healthcare burden. Additionally, brachytherapy delivers radiation dose from inside the body, allowing for better dose conformity to the target volume and sparing adjacent critical structures. As a result, brachytherapy may lead to reduced side effects and improved cosmetic outcomes compared to EBRT (Erven *et al*., 2008).

However, brachytherapy is not suitable for all breast cancer patients, particularly those with large tumour sizes, extensive disease involvement, or certain anatomical considerations. The selection of patients for brachytherapy depends on various factors, including tumour characteristics, surgical technique, patient anatomy, and treatment goals (Cozzi *et al*., 2022). Multidisciplinary collaboration between radiation oncologists, breast surgeons, and medical physicists is essential to determine the most appropriate treatment approach for each patient.

2.2.3.2 EXTERNAL BEAM RADIATION THERAPY

Radiation therapy usually starts six to eight weeks following surgery in patients receiving chemotherapy followed by surgery, or surgery followed by chemotherapy. Radiation therapy usually starts four to six weeks after the last chemotherapy cycle for patients whose initial course of treatment involves surgery and then chemotherapy. Simulation is a technique used in radiotherapy to mimic the patient's position during treatment. During this procedure, the site to be treated is marked, and this is first done before starting the radiotherapy. During simulation, the patient undergoes a non-contrast CT scan while in the treatment position. Temporary marks are made on the skin to aid radiation therapists in accurately positioning the patient for precise daily treatment delivery (Goto *et al*., 2022).

Radiation therapy is usually administered once a day, Monday through Friday, over a span of 3 to 6 weeks, depending on the stage of the patient's disease. In some cases, patients with certain types of breast cancer may be given accelerated partial breast irradiation (APBI), which involves twice-daily treatments for one week using a catheter placed inside the breast (Godette

et al., 2018). Additionally, a one-time intraoperative radiotherapy (IORT) treatment, performed during a lumpectomy, is available for selected patients. Other radiotherapy management approaches include adjuvant radiotherapy, post-mastectomy radiotherapy, and regional nodal irradiation.

2.2.3.3 ADJUVANT RADIOTHERAPY

Adjuvant radiotherapy is routinely administered following breast-conserving surgery (lumpectomy or partial mastectomy) to the residual breast tissue and regional lymph nodes (if indicated) to eradicate any remaining cancer cells and minimise the risk of local recurrence (Lin & Tripuraneni, 2011). The main objective of adjuvant radiotherapy is to eradicate tiny cancerous deposits and decrease the risk of cancer returning in the treated breast or chest wall. This treatment notably enhances rates of local control and overall survival for individuals with early-stage breast cancer who opt for breast-conserving therapy (Rampurwala *et al*., 2014).

2.2.3.4 POST-MASTECTOMY RADIOTHERAPY

Post-mastectomy radiotherapy, also known as chest wall irradiation, is recommended for selective patients with high-risk features, such as large primary tumours (>5 cm), involvement of multiple axillary lymph nodes, extracapsular extension, skin involvement, and close or positive surgical margins (Remick & Amin, 2023). The rationale for post-mastectomy radiotherapy is to eradicate residual tumour cells, prevent locoregional recurrence, and potentially improve long-term survival by eliminating microscopic disease burden in the chest wall and regional lymphatic drainage areas.

2.2.3.5 REGIONAL NODAL IRRADIATION

Regional nodal irradiation involves the delivery of radiotherapy to regional lymph nodes, including the internal mammary, supraclavicular, and infraclavicular lymph node regions, in addition to the primary breast or chest wall, particularly in patients with high-risk nodal involvement (Orsaria *et al*., 2014). The inclusion of regional nodal irradiation in the treatment plan aims to sterilise regional lymphatic pathways, reduce nodal recurrence rates, and enhance disease control in the axillary, internal mammary, and supraclavicular nodal basins.

2.3 TREATMENT PLANNING IN BREAST CANCER IRRADIATION

There are two components to treatment planning, first is the clinical treatment planning, which refers to selecting the treatment intent (either curative or palliative), the treatment modality, and the dose scheme for the treatment, which includes the total dose and dose per fraction. The dosing scheme selected for the treatment depends on the intent of the treatment. Second is the technical treatment planning which refers to how the patient is positioned or set up to receive the radiation, the angles at which the radiation beams are positioned, and how the MLCs will be used to shape the aperture or shape of the beams to achieve a highly conformal radiation dose distribution to the target volume (contoured by the oncologists in the clinical planning process) while protecting the critical organs (Xia *et al*., 2019). Treatment planning utilises sophisticated systems to model the radiation dose intended for the tumour. This optimisation aims to tailor the dose delivery to each patient by effectively targeting cancer cells while minimising exposure to surrounding organs.

2.3.1 PATIENT POSITIONING

In radiation therapy for breast cancer, precise patient positioning plays a pivotal role in achieving optimal treatment outcomes while minimising the risk to surrounding healthy tissues (Xiang *et al*., 2019). Patients are typically positioned in the supine position, lying on their back with arms raised above the head or alongside the body, depending on the treatment technique and target location. This positioning allows for a consistent setup across treatment sessions and facilitates access to the breast tissue for accurate dose delivery. Immobilisation devices such as vacuum bags or breast boards are often used to stabilise the patient and ensure reproducible positioning throughout the treatment course (Xiang *et al*., 2019). Additionally, breast compression techniques may be employed to reduce respiratory motion and flatten the breast tissue, enhancing dose uniformity and minimising setup errors.

To ensure precise target localisation and reproducibility, external skin markings and internal fiducial markers may be utilised, along with imaging modalities such as CT or cone-beam CT (CBCT) for accurate delineation of the treatment target. Patient comfort, reproducibility, and compliance with the prescribed treatment position are paramount, necessitating close communication and education to address any concerns or discomfort (Sasaki *et al*., 2023). Quality assurance measures, including regular imaging verification and setup checks using IGRT techniques, are implemented to verify patient setup and make necessary adjustments to ensure accurate treatment delivery. Through meticulous patient positioning and Immobilisation techniques, radiation oncology teams can optimise treatment efficacy while safeguarding the integrity of surrounding healthy tissues, ultimately enhancing the overall success of radiation therapy for breast cancer (Goyal & Kataria, 2014).

2.3.2 TREATMENT PLANNING SYSTEM

Treatment planning systems (TPS) play pivotal roles in the delivery of precise and effective radiation therapy treatment for cancer patients. One of the widely used TPS in the field is the

Eclipse treatment planning system, developed by Varian Medical Systems. Eclipse offers advanced capabilities for treatment planning, dose calculation, and plan optimisation to ensure optimal treatment outcomes. One of the key features of Eclipse is its use of the analytical anisotropic algorithm (AAA) for dose calculation, which provides high accuracy and reliability in predicting the dose distribution within the patient's anatomy. The Eclipse TPS allows the import of various imaging modalities such as CT, MRI, PET, and SPECT for treatment planning, and it enables the fusion of multiple imaging datasets to create a comprehensive 3D representation of the patient's anatomy, facilitating accurate target and organ at risk (de Martino *et al*., 2021).

Figure 2.3 is the user interface of the Eclipse treatment planning system. The TPS offers a range of visualisation and editing tools and different anatomical orientations to assist clinicians in accurately outlining tumour volumes and organs-at-risk (OARs) to assess the potential impact of radiation doses on them. The analytical anisotropic algorithm (AAA) considers the complex interactions of radiation beams with patient anatomy, including tissue heterogeneities, beam attenuation, and scatter, to compute dose distributions with high precision. It accounts for the anisotropic nature of radiation scattering, enhancing the accuracy of dose calculations, particularly in heterogeneous tissue regions based on dose-volume constraints, dose objectives, and clinical priorities to achieve personalised treatment goals (de Martino *et al*., 2021). The dose-volume histograms (DVHs) serve as a comprehensive statistical tool to assess plan quality, conformity, and organ sparing.

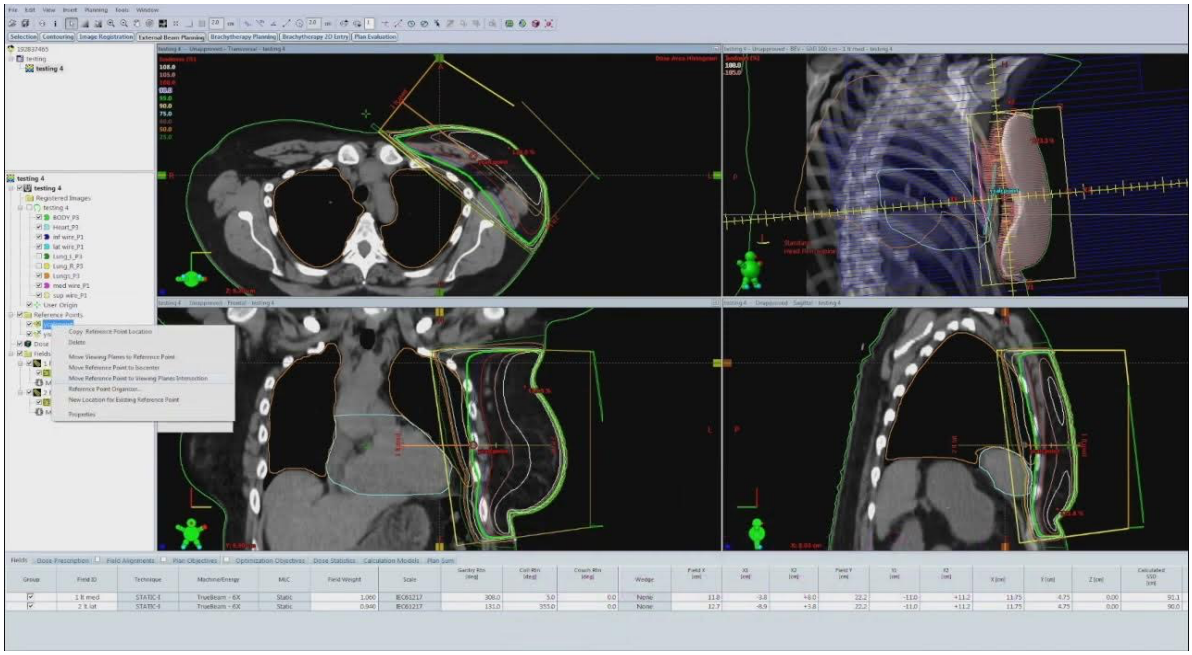

Figure 2.3 Eclipse treatment planning system user interface

2.3.3 TARGET VOLUME DELINEATION

The delineation of the target volume and organs at risk (OARs) in breast cancer radiotherapy involves a systematic approach that is based on tumour characteristics, anatomical considerations, and established guidelines. This comprehensive process ensures accurate treatment delivery while minimising the risk of geographical misses and treatment-related toxicities. The delineation process follows established clinical practice guidelines and consensus recommendations developed by expert panels and professional organisations. These guidelines provide standardised protocols and anatomical definitions to ensure consistency and reproducibility in target volume delineation across different treatment centres and practitioners (Lin *et al*., 2020). Examples of guidelines include those published by organisations such as the Radiation Therapy Oncology Group (RTOG), the European Society for Radiotherapy and Oncology (ESTRO), and the American Society for Radiation Oncology (ASTRO). These guidelines define the prospective targets as follows: gross tumour volume (GTV), clinical target volume (CTV), Planning Target Volume (PTV), and organs at risks (OAR).

2.3.3.1 GROSS TUMOUR VOLUME (GTV)

The GTV represents the visible extent of the primary tumour or residual tumour bed following surgical resection. It encompasses any macroscopic disease identified through diagnostic imaging, physical examination, and surgical findings. Delineating the GTV involves outlining the tumour or tumour bed in each imaging slice to accurately capture its three-dimensional extent. This may include scar tissue or surgical clips that serve as surrogate markers for the tumour location (Zhang *et al*., 2017).

2.3.3.2 CLINICAL TARGET VOLUME (CTV)

The CTV expands beyond the GTV to encompass areas at risk of microscopic disease spread or regional involvement based on the tumour's biological behaviour and anatomical considerations. CTV delineation takes into account factors such as tumour histology, tumour grade, lymphovascular invasion, margin status, and tumour location within the breast (Zhang *et al*., 2017).

Commonly included structures within the CTV for breast cancer radiotherapy may comprise the entire residual breast tissue, regional lymph nodes (which include internal mammary nodes and axillary nodes), and adjacent anatomical structures susceptible to tumour involvement.

2.3.3.3 PLANNING TARGET VOLUME (PTV)

The PTV further extends the target volume to accommodate uncertainties associated with treatment setup variability, patient motion, and internal organ motion during treatment delivery (Zhang *et al*., 2017).

PTV delineation incorporates additional margins around the GTV and CTV to ensure adequate coverage of the target volume under varying treatment conditions while minimising the risk of

underdosing. Margin expansions are typically based on considerations such as setup error, patient Immobilisation accuracy, organ motion, and beam penumbra.

2.3.3.4 ORGANS AT RISK (OARS)

Organs at risk (OARs) are vital structures whose function or integrity must be preserved to minimise treatment-related toxicities. Common OARs in breast radiotherapy include the lungs, heart, contralateral breast, skin, ribs, and soft tissues (Bisello *et al*., 2022). Figure 2.4 shows the transverse view of a contoured CT image indicating the various organs at risk. Accurate delineation and contouring of these structures guide treatment planning to minimise radiation exposure and reduce the risk of radiation-induced complications. For instance, minimising lung dose helps prevent radiation pneumonitis or fibrosis, while techniques like heart-sparing radiation therapy mitigate the risk of cardiovascular complications (Bisello *et al*., 2022). Strategies such as customised shielding and beam modulation ensure a balance between target coverage and OAR protection, optimising treatment outcomes and minimising treatment-related adverse effects in breast cancer patients undergoing radiotherapy.

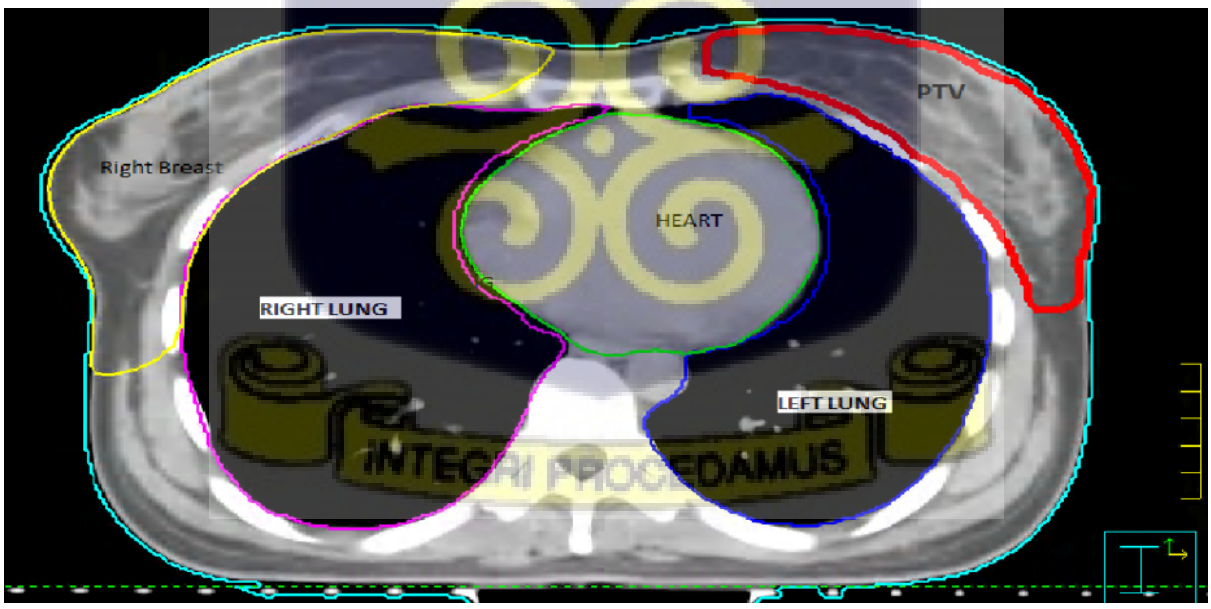

Figure 2.4 Transverse view of a contoured CT image indicating the target volume and organs at risk.

2.3.4 TREATMENT PLANNING TECHNIQUES

2.3.4.1 3D CONFORMAL RADIATION THERAPY (3D-CRT)

Breast irradiation methodologies have evolved from 2-dimensional to 3-dimensional conformal radiation therapy (3D-CRT) and even more improved techniques. The 3DCRT has long been the traditional treatment planning technique for breast irradiation (Sonnik *et al*., 2007). 3D-CRT incorporates detailed three-dimensional imaging, such as computed tomography (CT) scans, to accurately visualise the tumour and surrounding anatomy. By precisely delineating the target volume and critical structures, such as organs at risk (OARs), medical physicists can design treatment plans that deliver therapeutic doses to the tumour while sparing adjacent healthy tissues (Chen *et al*., 2020). This is achieved through the optimisation of radiation beam angles, shapes, and intensities, ensuring that the radiation conforms closely to the shape and size of the tumour. The 3D-CRT treatment planning involves using a pair of posterior parallel opposing tangential fields (medial and lateral). The gantry angles are chosen firstly, based on how the divergence of posterior edges of the two tangential beams match as indicated in Figure 2.4 to avoid irradiating the contralateral breast and as well minimise the ipsilateral lung and heart area in the field and secondly to provide the optimal radiation dose coverage to the PTV (Gerardina *et al*., 2016).

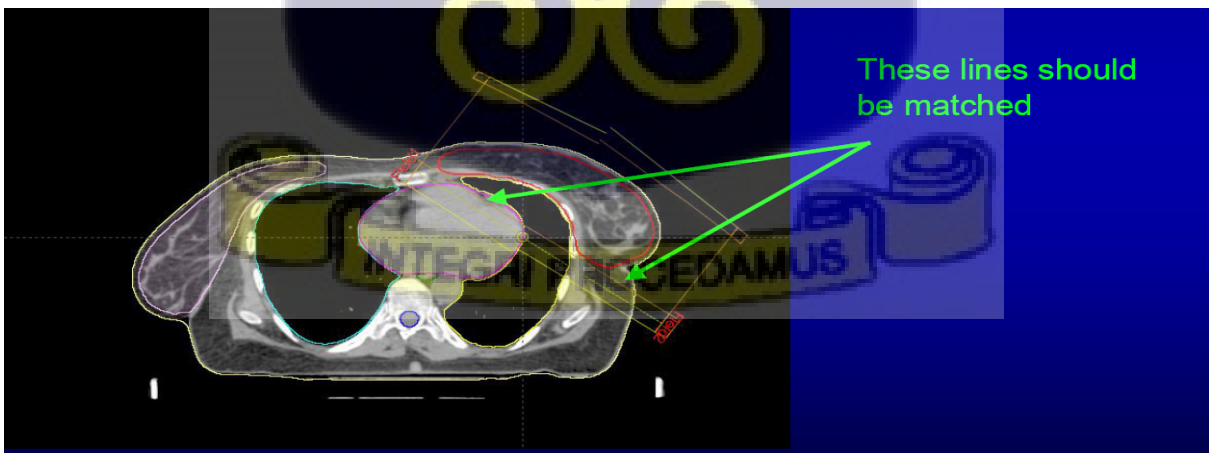

Figure 2.5 Tangential beam arrangement ((Svet Zdravia, 2014).

Multileaf collimators (MLCs) are essential components used in three-dimensional conformal radiation therapy (3D-CRT). They are composed of movable leaves that adjust the shape of the radiation beam to precisely conform to the target area, thereby minimising exposure to surrounding healthy tissues. This technology enhances treatment accuracy and reduces side effects for patients undergoing radiation therapy (Rehman *et al*., 2018). The radiation beam can be precisely matched to the contours of the target volume and possible regional lymph nodes to minimise radiation exposure to healthy organs, which is essential for reducing treatment-related toxicities and optimising outcomes. This is depicted in Figure 2.5

Wedges are another component commonly utilised in 3D-CRT to optimise dose distribution and homogeneity across the target volume. Wedges, either physical or dynamic, are employed in the treatment beam path to modulate the radiation dose, typically by attenuating the radiation beam in certain directions. Wedges compensate for differences in tissue thickness and density, resulting in improved dose homogeneity (Syam *et al*., 2018).

However, this method presents difficulties in achieving a uniform dose distribution across the target area and can inadvertently deliver unwanted doses to the skin and nearby organs, leading to both immediate and long-term toxicities. To overcome these issues, advanced and sophisticated radiation therapy technologies have over the years been developed. These innovations aim to enhance dose uniformity within the target and minimise high-dose exposure to surrounding organs-at-risk (OARs).

2.3.4.1.2 PRONE POSITIONING FOR BREAST 3D-CRT

Recent clinical studies indicate that positioning patients prone during breast radiation can better protect normal organs, especially in individuals with larger or pendulous breasts. Specialised breast boards have been designed to maintain a stable prone position, allowing the breast to hang freely from the thoracic wall and away from underlying organs. Generally, the prone

technique as shown in Figure 2.6 enhances dose homogeneity (Deseyne *et al*., 2017). However, the prone position can hinder target coverage at the medial and lateral breast borders near the chest wall due to limited beam access. Despite this, studies have consistently shown a significant reduction in lung doses. The impact on heart sparing is less definitive, as the heart shifts anteriorly in this position. Additionally, the risk of skin breakdown (epidermolysis) is decreased by eliminating skin folds (Deseyne *et al*., 2017). The impact of prone positioning on planning target volume (PTV) margins around the clinical target volume (CTV) in treatment planning is two-fold. Firstly, the breathing motion is less pronounced in this position, resulting in smaller intra-fraction motion. However, patient setup variations can be significantly larger, which increases inter-fraction variation.

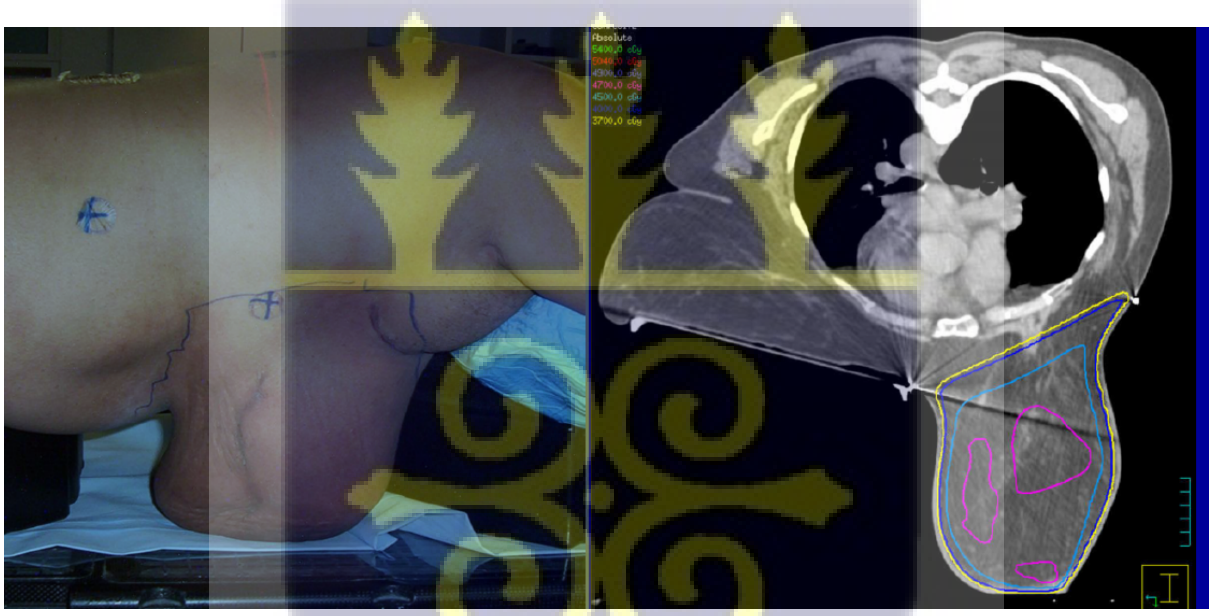

Figure 2.6 Prone position for 3D-CRT irradiation (Svet zdravia, 2014).

2.3.4.2 FIELD IN FIELD (FIF)

In an attempt to reduce the challenge of dose inhomogeneity associated with the 3D-CRT technique, the FIF approach was introduced. Fields are generated using multileaf collimator (MLC) leaves positioned strategically to cover areas where the dose to the breast significantly exceeds the prescribed dose, known as hot spots (Nakamura *et al*., 2011). With the FIF

technique, the primary fields are set up in the same manner as the 3D-CRT. It covers the entire breast or tumour bed. The shape and size of this field are determined based on the target volume and the desired dose distribution. The primary field is typically shaped to encompass the PTV while sparing nearby critical structures as much as possible. Within the primary field, subfields or segments are defined to further shape the radiation dose distribution (Lee *et al*., 2008).

These subfields are usually smaller weighted fields that are designed to deliver additional radiation dose to specific areas within the target volume that require higher doses or to compensate for irregularities in the target shape as well as reduce the doses to segments within the target volume receiving high doses also known as hotspots. The shape and size of the subfields are optimised to achieve the desired dose distribution. The technique allows for better dose conformity to the target volume, resulting in improved tumour coverage. By utilising the subfields and beam modulation, dose heterogeneity within the target volume can be minimised, which can lead to a more uniform dose distribution.

The FIF technique, Figure 2.7, can be adapted to accommodate variations in breast size, shape, and tumour location, allowing for personalised treatment which will yield sparing nearby critical structures (such as the heart, lungs, and contralateral breast), and reducing the risk of radiation-related side effects.

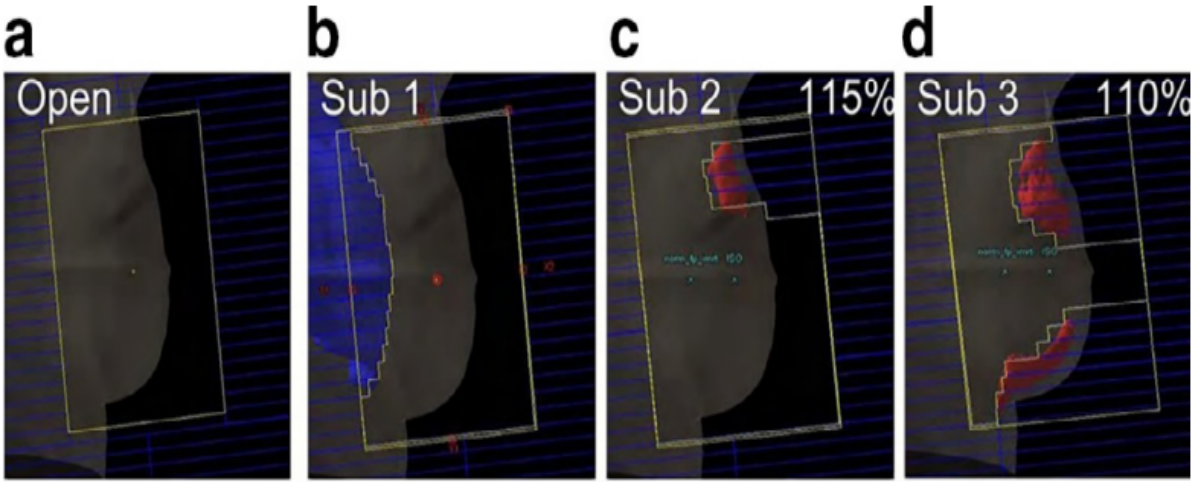

Figure 2.7 Right-anterior oblique portal views of FIF technique. (a) Main field without MLC blocking. (b) Drawing MLC to block out lung. (c) Drawing MLC to block out 115% isodose cloud. (d) Drawing MLC to block out 110% (Yoder *et al*., 2019).

2.3.4.3 INTENSITY MODULATED RADIATION THERAPY (IMRT)

Precision is paramount in radiation therapy. IMRT is an advanced radiation therapy technique used to deliver precise and highly conformal doses of radiation to cancerous tumours while minimising the dose to surrounding healthy tissues. The principle behind IMRT lies in the ability to modulate the intensity of the radiation beams to achieve a customised dose distribution that conforms to the shape of the tumour (Suyan *et al*., 2021). IMRT represents a revolutionary advancement in radiation oncology, which harnesses cutting-edge technology to customise radiation delivery to the unique contours of each patient's tumour. Unlike traditional forward planning techniques like the 3D-CRT, which delivers uniform doses of radiation, IMRT is an inverse planning technique that uses multiple radiation fields, as shown in Figure 2.8, with specialised treatment planning software, which optimises the radiation dose to achieve the desired distribution. The software employs complex algorithms to calculate the optimal intensity of radiation beams from various angles (Chen *et al*., 2020). The intensity of each beam is modulated across multiple smaller beamlets, each with varying intensity levels. The motion

of the MLCs allows for these beamlets to be deposited in areas of the tissue to promote a homogenous dose distribution in the tissue. It employs different delivery methods such as step-and-shoot (or segmental), sliding window (dynamic), or compensator-based methods.

There are numerous potential sources of errors in IMRT planning and delivery. During treatment planning, errors may stem from factors such as modelling MLC leaf ends, MLC tongue-and-groove effects, leaf and collimator transmission, collimator and MLC penumbra, compensator systems including scattering, beam hardening, and alignment issues, output factors for small field sizes, head backscatter, and off-axis profiles (Miften *et al*., 2018). Additional choices may include the selection of grid size for dose calculation and the incorporation of correct factors for tissue heterogeneity. These sources of errors have necessitated patient-specific quality assurance programmes aimed at checking the accuracy of the IMRT plans to detect clinically relevant errors in the radiation delivery process and ensure good agreement between calculated dose during planning and measured dose during treatment (Miften *et al*., 2018).

According to recommendations from the American Association for Physicist in Medicine Task Group No. 218, the predefined acceptance criterion for IMRT patient specific quality assurance is ±5%. If upon IMRT PSQA, the difference in dose between the planned and measured dose exceeds 5%, the decision will be to refrain from proceeding with treatment based on the specified plan (Miften *et al*., 2018).

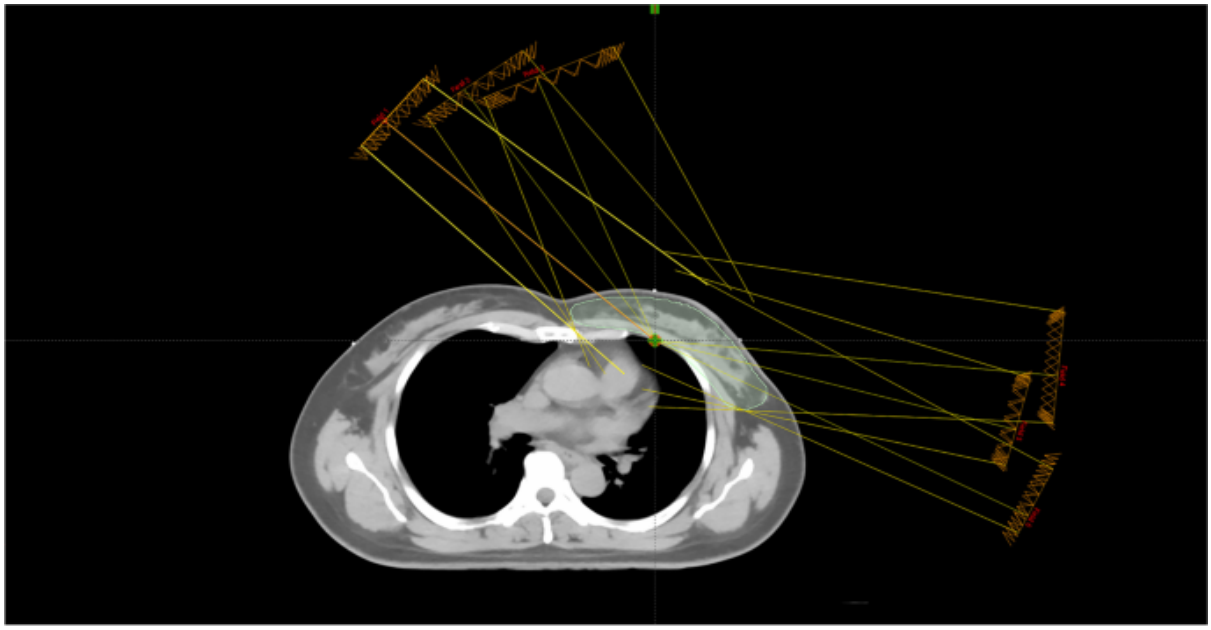

Figure 2.8 Transverse view of a CT image indicating the beam arrangement for intensity modulated radiation therapy.

2.3.4.4 VOLUMETRIC ARC THERAPY (VMAT)

Volumetric-modulated arc therapy (VMAT) is an advanced technique used for breast irradiation. It delivers the radiation in a continuous arc around the patient. In Figure 2.9, the yellow semi-circle indicates the continuous motion of the beam angle both in the clockwise and anti-clockwise direction. This method allows for precise modulation of radiation beams to conform closely to breast tissues while sparing healthy tissues like the heart, lungs and contralateral breast as shown in Figure 2.9. VMAT improves treatment efficiency and patient comfort by reducing session times and adapting to individual patient anatomy, hence, minimising the need for repositioning. It offers distinct advantages over traditional methods by optimising dose distribution based on tumour characteristics, thereby reducing side effects and enhancing treatment outcomes.

Clinical studies demonstrate VMAT's effectiveness in breast cancer treatment, highlighting its ability to deliver precise doses with lower toxicity compared to conventional techniques. Ongoing research by Wang *et al.* in 2022, aims to refine VMAT parameters to improve further dose precision and long-term treatment results for breast cancer patients. VMAT represents a significant advancement in radiation therapy, combining precision with efficiency to offer personalised treatment that enhances quality of life and therapeutic effectiveness in breast cancer management.

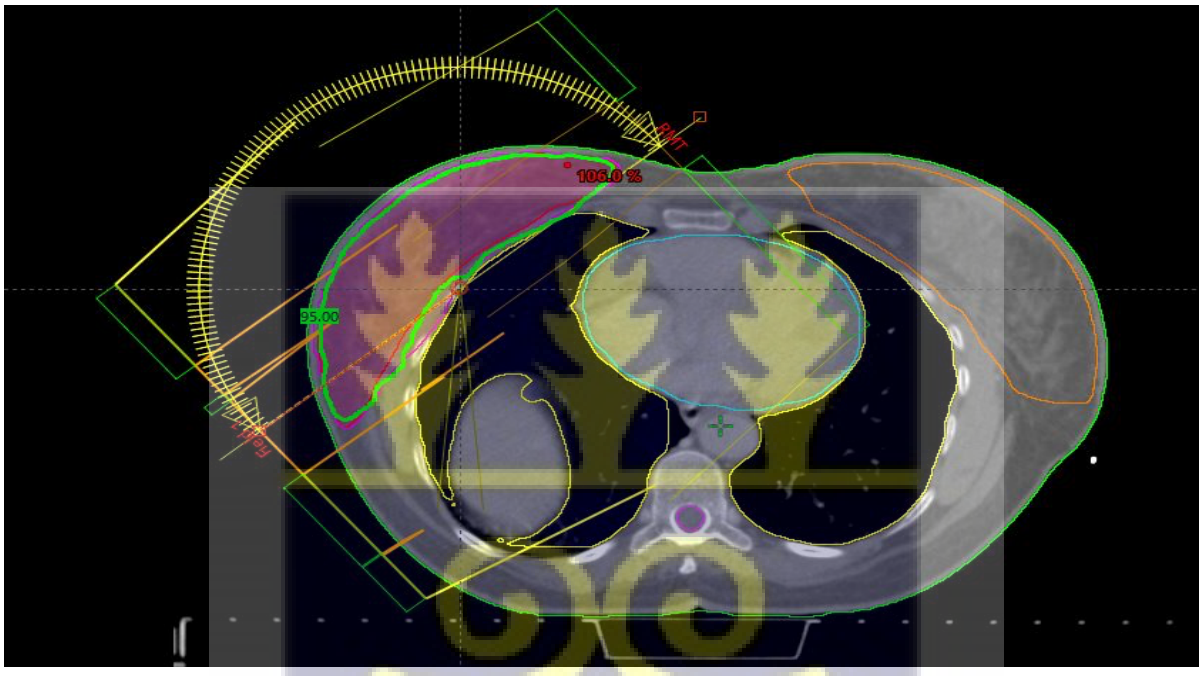

Figure 2.9 Transverse view of a contoured image indicating the arc direction for a VMAT plan.

2.3.4.4 HYBRID PLANNING TECHNIQUES

Combining models in engineering and physical sciences offers the benefit of integrating strengths from multiple models to address the limitations of individual ones. Each model contributes unique strengths and weaknesses, and their integration offers a comprehensive perspective of the system, enhancing the accuracy and robustness of outcomes (Karaca, 2022). It is in this perspective that there has been a several proposals in radiotherapy to hybridise 3DCRT, IMRT, and VMAT models. Such a hybrid approach could bring several benefits to

breast cancer radiotherapy. The hybrid planning techniques leverage the complementary strengths of the individual modalities to tailor treatment plans according to individual patient characteristics to optimise dose distribution and spare critical structures. One key advantage of hybrid planning techniques is their flexibility to adapt to patient-specific anatomical and clinical consideration. Treatment plans can be customised based on factors such as tumour size, location, and proximity to critical structures (Karaca, 2022). This personalised approach enhances treatment precision and efficacy, leading to improved clinical outcomes and quality of life for patients undergoing radiation therapy.

2.3.4.4.1 COMBINING 3D-CRT WITH IMRT

Combining the well-established principles of 3D conformal radiation therapy (3D-CRT) with the advanced dose conformity capabilities of intensity-modulated radiation therapy (IMRT) represents a significant advancement in radiation oncology (Voyant *et al*., 2024). This hybrid approach seamlessly integrates the simplicity and familiarity of 3D-CRT with the refined dose modulation of IMRT.

In the hybrid technique of 3D-CRT with IMRT, the foundation is laid upon the use of two opposed tangential open beams characteristic of 3D-CRT (Rudat *et al*., 2011). These beams are carefully positioned to target the tumour volume while minimising radiation exposure to surrounding healthy tissues. The tangential geometry ensures comprehensive coverage of the target area; a feature long appreciated for its simplicity and efficacy in tumour targeting. Complementing the tangential beams of 3D-CRT are two inverse-planned IMRT beams. Unlike traditional IMRT techniques, where multiple beams are utilised, the hybrid approach strategically incorporates a limited number of IMRT beams to augment dose conformity (Suyan *et al*., 2021).

Integrating 3D-CRT and IMRT in this hybrid technique results in an optimised dose distribution characterised by a balance between target coverage and normal tissue sparing. The tangential beams of 3D-CRT provide robust coverage of the tumour volume, while the IMRT beams deliver highly conformal doses, sculpting the radiation dose to match the contours of the tumour precisely (Karaca, 2022).

2.3.4.4.2 COMBINING VMAT WITH 3D-CRT

Volumetric-modulated arc therapy (VMAT) stands as a pioneering radiation therapy technique, revolutionising treatment delivery through its rotational approach and dynamic modulation of radiation beams. When integrated with the established principles of 3D conformal radiation therapy (3D-CRT), VMAT augments treatment precision, efficiency, and patient comfort, thus setting a new standard in radiation oncology (Bi *et al*., 2022).

At the core of VMAT lies its ability to deliver radiation in a continuous arc trajectory around the patient. Unlike conventional static beam techniques, VMAT dynamically adjusts the gantry rotation speed, dose rate, and multileaf collimator (MLC) positions throughout the arc, allowing for precise modulation of the radiation dose (Voyant *et al*., 2024). This dynamic approach ensures highly conformal dose distribution, sculpting the radiation dose to match the intricate contours of the tumour volume. When combined with 3D-CRT, VMAT synergistically enhances treatment precision and efficacy (Lin *et al*., 2015). The tangential beams of 3D-CRT provide robust coverage of the tumour volume, while VMAT further refines the dose distribution, optimising dose homogeneity and target coverage.

2.4.0 PLAN EVALUATION

Treatment plan evaluation (TPE) is a major step in RT planning that assesses the quality of a plan using either physical or biological endpoints (Hernandez *et al*., 2020; Boughalia *et al*., 2018). The biological endpoints involve the use of models with biological indices such as tumour control probability (TCP) and normal tissue complication probability (NTCP) (Kamfosi, 2018). However, due to the lack of clinical data required to validate treatment plans, physical endpoints are often used (Khan, 2010). Physical endpoints involve physical tools such as isodose curves and dose-volume histogram (DVH) which are commonly used to evaluate the dose distribution in a plan (Barrett *et al*., 2009 & Petrova *et al*., 2017).

2.4.1 DOSE-VOLUME HISTOGRAM (DVH)

Dose-volume histograms (DVHs) are graphical representations used in radiation therapy to visualise the distribution of radiation dose received by specific volumes of tissue or organs within the patient's body. DVHs plot the cumulative volume of tissue receiving a given dose or greater in the Y-coordinate against the radiation dose levels, typically expressed in gray (Gy) or percentage of the prescribed dose (Gossman & Bank, 2010) in the X-coordinate as shown in Figure 2.10. The DVH provides valuable quantitative information about the dose distribution within the target volume and surrounding normal tissues, aiding in treatment planning, evaluation and optimisation. By analysing the DVH, radiation oncologists and medical physicists can assess critical dose-volume parameters such as the minimum dose (Dmin), maximum dose (Dmax), mean dose (Dmean), and dose to specific volumes or percentages of tissue (e.g., D95, D50). These parameters help quantify the dose coverage of the target volume and the extent of radiation exposure to adjacent critical structures (de Martino *et al*., 2021).

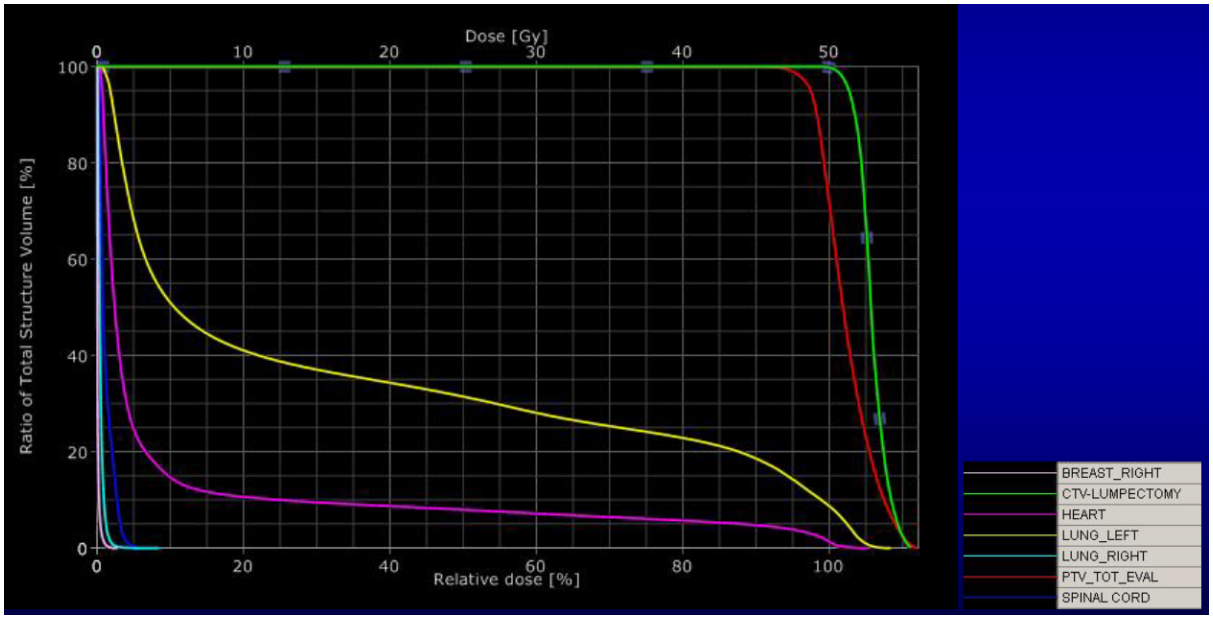

Figure 2.10 Dose volume histogram for a breast plan

2.4.2 HOMOGENEITY INDEX (HI)

The homogeneity index (HI) quantifies the uniformity of dose distribution within the target volume. It is calculated as the ratio of the maximum dose (D_{max}) to the prescription dose (D_{pres}) within the target volume (Kataria *et al*., 2012). A lower HI indicates a more homogeneous dose distribution, which is desirable as it reduces the risk of under- or overdosing within the target volume. Achieving optimal dose homogeneity is crucial for ensuring effective tumour control while minimising the risk of normal tissue complications. The RTOG and ICRU 83 respectively define HI as a ratio of the maximum dose (Dmax) in the target volume to the prescribed dose (Dp), (Shaw *et al*., 1993).

Mathematically, homogeneous index (HI) can be calculated as 2.1;

$$\frac{D2\%-D98\%}{D50\%} \qquad (2.1)$$

where;

D2% is the dose to 2% of the volume of the PTV.

D98% is the dose to 98% of the volume of the PTV.

D50% is the dose to 50% of the volume of the PTV.

2.4.3 CONFORMITY INDEX (CI)

The conformity index (CI) assesses the degree to which the prescribed dose conforms to the target volume while sparing surrounding healthy tissues. It is calculated as the ratio of the volume of the target covered by the prescription isodose line to the total target volume, normalised by the volume receiving the prescription dose (Petrova *et al*., 2017). A higher CI indicates better conformity, with the prescribed dose closely matching the target volume. CI is essential for evaluating treatment plans' ability to deliver adequate doses to the target while minimising doses to adjacent critical structures.

The Conformity Index can be calculated as 2.2;

$$\frac{V95\%}{Vtreated} \qquad (2.2)$$

where;

V95% is the volume covered by 95% of the prescribed dose and

Vtreated is the Volume of the target being treated.

2.5 COMPARATIVE STUDIES (WORK DONE BY OTHERS)

Comparative studies between 3D conformal radiation therapy (3D-CRT) and intensity-modulated radiation therapy (IMRT) have consistently shown that IMRT offers superior dose distribution. For instance, Zhou *et al*. (2019) demonstrated that IMRT provides a more homogeneous dose distribution within the tumour while also sparing the heart and lungs more

effectively compared to 3D-CRT. Li *et al*. (2020) found that IMRT could significantly reduce the dose to organs at risk (OARs) by adjusting the beam intensity and angles, a capability not achievable with the fixed beam geometry of 3D-CRT. This enhancement in dose conformity and sparing of normal tissues is crucial for minimising late side effects.

Ezzell *et al* in (2021) reported that VMAT offers improved dose distribution due to its rotational delivery approach in a study where they compared 3D-CRT and VMAT. VMAT's ability to continuously adjust dose rates and gantry angles throughout the treatment arc allows for better conformation to complex tumour shapes and a reduction in dose to surrounding tissues. Baker *et al*. (2022) also confirmed that VMAT generally results in a more homogeneous dose distribution and a reduced volume of normal tissue receiving high doses compared to 3D-CRT. This advantage is particularly notable in breast irradiation, where VMAT can effectively reduce the dose to the contralateral breast and chest wall.

A comparative study between VMAT and IMRT by Khan *et al* in (2022) reported that VMAT typically outperforms IMRT in treatment efficiency and plan quality. The continuous radiation delivery ability of VMAT helps to reduce the treatment time as compared to IMRT, which often requires multiple static beams. Martin *et al*. (2023) highlighted that while VMAT may offer better efficiency and reduced treatment times, IMRT is still favoured for its precision in dose distribution for complex or irregularly shaped tumours. The choice between these techniques should balance VMAT's advantage in dose distribution with its complexity and equipment demands.

Hybrid techniques, such as combining IMRT with 3D-CRT or VMAT, have shown promising results. Jiang *et al*. (2023) explored these hybrid approaches and found that integrating IMRT with 3D-CRT could optimise dose distribution by combining the strengths of both techniques. For example, the tangential beams of 3D-CRT provide broad tumour coverage, while IMRT's

precision enhances dose conformity. This hybrid method results in improved dose distribution and critical structure sparing.

2.6 ADVANCED TECHNIQUES AND INNOVATIONS

2.6.1 INNOVATIONS IN VMAT

Recent advancements in VMAT include the integration of knowledge-based planning systems. These systems use historical treatment data and machine learning algorithms to predict optimal treatment plans based on patient-specific characteristics. A study by Zhang *et al*. (2023) demonstrated that knowledge-based planning can significantly reduce planning time and improve dose distribution accuracy by leveraging previous patient data to enhance plan quality and consistency. This approach not only streamlines the planning process but also optimises dosimetric outcomes by incorporating learned patterns from previous treatments.

Also, Adaptive radiotherapy (ART) in conjunction with VMAT has emerged as a promising technique to address anatomical and physiological changes during treatment. Research by O'Neill *et al*. (2022) highlighted that ART allows for real-time adjustments of the treatment plan based on changes in tumour size or patient anatomy, leading to improved dose conformity and reduced toxicity. By using daily imaging data to adapt the treatment plan, ART ensures that the delivered dose remains accurate and effective throughout therapy.

2.6.2 INNOVATIONS IN IMRT

Advances in IMRT delivery have focused on improving modularity and flexibility. Modular IMRT systems, as explored by Patel *et al*. (2023), enhance dose conformity by allowing for finer control over beam modulation and delivery. These systems use advanced beam-shaping technologies and high-resolution multi-leaf collimators (MLCs) to deliver highly conformal

doses to the target while minimising dose to surrounding healthy tissues. Modular IMRT systems also enable more precise treatment of complex tumour geometries.

Machine learning algorithms have been increasingly applied to optimise IMRT plans. A study by Wang *et al*. (2023) demonstrated that incorporating machine learning models into the planning process could enhance dose distribution and improve plan quality by predicting and adjusting for potential dosimetric discrepancies. These advancements contribute to more efficient and accurate treatment planning, reducing manual intervention and potential for human error.

2.6.3 INNOVATIONS IN HYBRID TECHNIQUES

Combining the principles of knowledge-based planning with hybrid techniques, such as IMRT and 3D-CRT, has shown potential in optimising treatment outcomes. Research by Li *et al*. (2024) indicated that integrating knowledge-based approaches with hybrid techniques allows for more precise customisation of treatment plans. This integration leverages data-driven insights to balance the strengths of multiple modalities, improving dose distribution and critical structure sparing. Adaptive planning approaches that incorporate hybrid techniques are being explored to enhance treatment precision. A study by Kim *et al*. (2023) found that adaptive hybrid planning, which adjusts for anatomical changes using a combination of IMRT and VMAT, can improve dose conformity and reduce toxicity. This method allows for real-time adjustments based on patient-specific changes, optimising treatment delivery throughout the course of therapy.

2.7 EMERGING TECHNOLOGIES

2.7.1 PROTON THERAPY

Proton therapy represents a significant advancement in radiation therapy due to its ability to deliver precise doses with minimal exit dose. Research by Zhang *et al*. (2023) has highlighted the potential of proton therapy for breast cancer treatment, particularly in reducing dose to surrounding healthy tissues and critical structures. Proton therapy's ability to deliver high doses to the tumour while sparing normal tissues can lead to improved treatment outcomes and reduced long-term side effects. A comparative study by Jones *et al*. (2024) investigated proton therapy versus conventional photon-based techniques, including VMAT and IMRT. The study found that proton therapy offers superior dosimetric outcomes in terms of dose conformity and normal tissue sparing. However, the high cost and availability of proton therapy facilities remain challenges that need to be addressed to make this technology more accessible.

2.7.2 MR-GUIDED RADIATION THERAPY

Magnetic Resonance-guided radiation therapy (MRgRT) combines the precision of MRI imaging with radiation delivery. Research by Wang *et al*. (2024) highlighted the advantages of MRgRT in breast cancer treatment, including improved tumour delineation and real-time monitoring of anatomical changes. MRgRT's ability to provide high-resolution imaging and adapt treatment plans in real-time enhances dose accuracy and reduces radiation exposure to healthy tissues. A study by Patel *et al*. (2024) assessed the clinical impact of MRgRT compared to conventional techniques. The findings indicated that MRgRT improves treatment precision, reduces setup errors, and enhances patient outcomes by allowing for adaptive adjustments based on daily imaging. This technology represents a significant innovation in radiation therapy, offering new opportunities for personalised treatment and improved patient care.

CHAPTER THREE

3.0 METHODOLOGY

3.1 INTRODUCTION

Chapter three outlines the method that guided the study, it includes the various key aspects such as the materials for the study, the study design employed, the study population used, the sampling technique employed, the rationale for determining the sample size, the inclusion and exclusion criteria used, tools for data collection, procedures for data collection, management, and analysis, ethical considerations, as well as plans for the dissemination of information.

3.2 STUDY LOCATION

This research work was conducted at the National Radiotherapy Oncology and Nuclear Medicine Centre (NRONMC) of the Korle-Bu Teaching Hospital. It is the largest of three radiotherapy centres in the country. The Department has been accredited internationally as a training centre for medical physicists, radiation therapy technologist (RTTs), and radiation oncologists by the International Atomic Energy Agency (IAEA) and locally by the Allied Health Professions Council for training students of the Biomedical and Allied Health Sciences Department of the University of Ghana. The Centre houses a linear accelerator and a cobalt-60 teletherapy machine for cancer treatment, a GE computer tomography scanner, a high dose rate brachytherapy Afterloader, and a Chemo suite for administering Chemotherapy to cancer patients. All data presented in this study were acquired following the approval of ethical clearance. The reference number for the ethical clearance received was Ref: ECBAS 053/23-24 and is shown on page 121 in the appendix.

3.3 STUDY DESIGN

The study is a retrospective cross-sectional study wherein retrospective patient CT images were retrieved from the treatment planning system (TPS), which was originally utilised for treatment planning. It included 50 patients with 25 intact breast cancer cases and 25 chest-wall (breast

cancer patients who have undergone mastectomy) cases. The 25 intact breast cancer cases were further sectioned into 15 left-sided breast cancer cases and 10 right-sided breast cancer cases. The 25 chest-wall cases were also sectioned as 15 left-sided breast cancer cases and 10 right-sided breast cancer cases. Four plans: 2 Hybrids with varying beam arrangements, an IMRT and a VMAT were created on each dataset. The two hybrid plans were created using a dose varying ratio of 80% : 20% thus, for the open field : optimised plan. A dose of 50 Gy in 25 fractions was used for all the plans.

3.4 INCLUSION AND EXCLUSION CRITERIA

3.4.1 Inclusion Criteria

All breast cancer patients, both with either chest wall or intact breast cases, referred to the centre for radiotherapy during the period of January, 2019 to March, 2024 were considered for the study.

To boost the statistical power for cardiac indices, more left-sided patients were selected.

3.4.2 Exclusion Criteria

Patients with positive lymph nodes or supraclavicular involvement and metastasis were not included in the study. Also, male breast cancer patients were not considered.

3.5 STUDY POPULATION

The study population included all breast cancer patients who were referred for radiation therapy at the NRONMC and satisfied the selection criteria from January 2019 to March 2024. This timeframe provided a sufficient volume of data for the study's analysis.

3.6 SAMPLING METHOD

This study employed the simple random sampling technique to eliminate bias and guarantee a representative sample. Each patient was assigned a number, and a research randomiser was employed to select these numbers randomly.

3.7 SAMPLE SIZE

The sample size used in this research was estimated using Slovin's formula. This method is widely recognised for determining sample sizes when the population size is known and when the study demands a specific margin of error. The formula in equation 3.1 is expressed as:

$$n = \frac{N}{1+Ne^2} \tag{3.1}$$

where:

(n) is the estimated sample size,

(N) is the total population size,

(e) is the margin of error, which for this study is set at 0.05, representing a 95% confidence interval.

For this study, data from case presentations between January 2019 to March 2024 were used to estimate the sample size. The population size (N) was determined based on the average number of cases per year and extrapolated over the study period. Given that the study spans a period of 8 months within this timeframe, the total number of cases was proportionally adjusted to reflect this period.

3.8 MATERIALS

All treatment plans were generated using the Eclipse treatment planning system version 13.6 (Varian Medical Systems, Palo Alto, CA, USA). Other documents, such as ICRU report 50, report 62, report 83, and RTOG constraints, served as reference materials and protocols that guided the planning and contouring process.

3.8.1 ECLIPSE TREATMENT PLANNING SYSTEM VERSION 13.6

The Eclipse Treatment Planning System (TPS) is a software solution developed by Varian Medical Systems, designed to assist in the planning and optimisation of radiation therapy treatments. This study used Eclipse TPS version 13.6 to develop and optimise treatment plans for the cases under investigation. Version 13.6 of the TPS uses sophisticated dose calculation algorithms, such as the anisotropic analytical algorithm (AAA) and Acuros XB, which allow for highly accurate dose distributions, even in heterogeneous tissues, as shown in Figure 3.1:

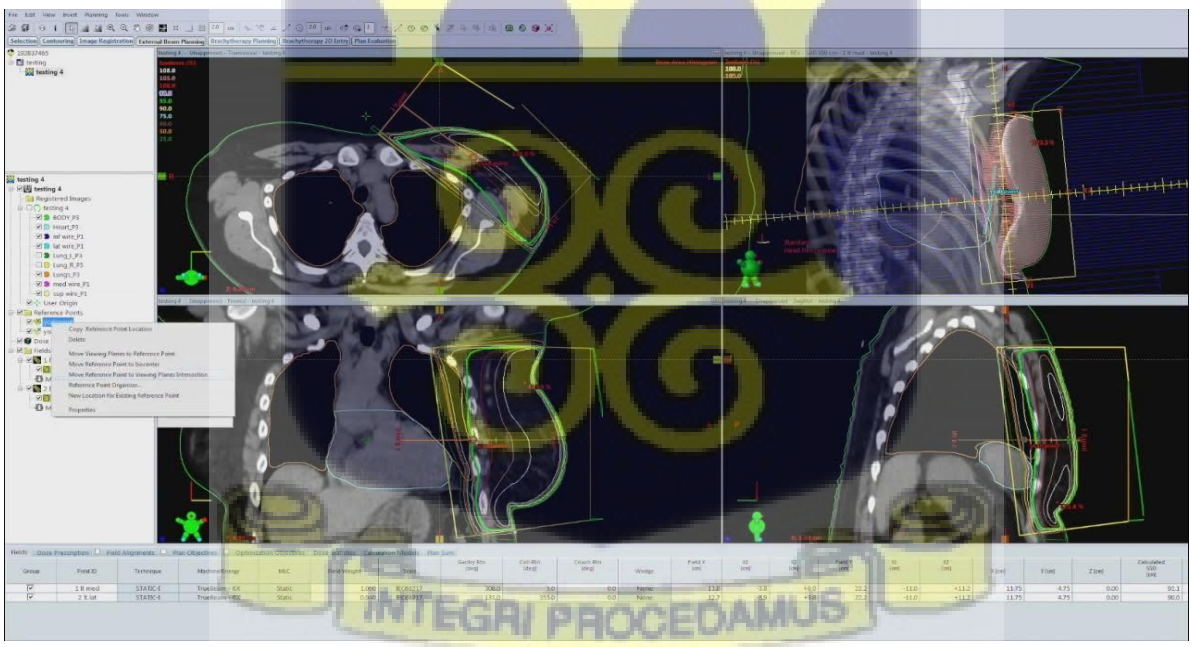

Figure 3.1 Eclipse treatment planning system user interface

The system's advanced features facilitated the creation of highly conformal plans tailored to each patient's specific anatomical and clinical characteristics. The accuracy of the dose calculation

algorithms and the flexibility of the plan optimisation tools were crucial for achieving the research objectives.

3.9 PROCEDURE AND DATA COLLECTION

3.9.1 CT SIMULATION

All patients underwent a non-contrast computed tomography (CT) simulation of 0.25-mm thickness reconstruction using a GE Discovery CT590 RT (16 slice count; software version 11BW). Patients were scanned in the supine position. Immobilisation devices such as the breast board were used for ease of access to the breast, to ensure there is patient comfort and good reproducibility of patient positioning. An armrest was used to position the arms above the head and out of the treatment field,as shown inFiguire 3.2. The knee rest was also used to ensure comfort and pelvic stability. The CT images were stored in a DICOM (Digital Imaging and Communication in Medicine) format and images were transferred to the Eclipse planning system version 13.6 (Varian Medical System, Palo Alto, CA) for the planning process.

Figure 3.2 Patient being simulated on a breast board for CT imaging.

3.9.2 VOLUME DELINEATION

3.9.2.1 DOSE STRUCTURES/ORGANS AT RISK

In the analysis of each dataset, a radiation oncologist meticulously contoured regions of interest, including the ipsilateral lung, contralateral lung, entire lung volume, contralateral breast, heart, and spinal cord, on a slide-by-slide basis. This detailed contouring was essential for providing a comprehensive volumetric representation of these anatomical structures. Although these structures are not the primary targets of treatment, their delineation is crucial for monitoring the radiation exposure received by each of them.

3.9.2.2 TARGET VOLUMES

The clinical target volume (CTV) for both the intact breast and the chest wall was delineated with specific margins: the superior margin was defined by the head of the supraclavicular region, while the inferior margin extended 2 cm below the inframammary fold. The lateral margin was established along the anterior axillary line, and the midstream line served as the inner margin. In cases involving the chest wall, additional structures such as the ribs, pectoral muscles, and intercostal muscles were incorporated into the CTV contour. Figure 3.3 shows a transverse view of a contoured CT image showing the CTV and the delineated organs at risk. This contouring was conducted in accordance with the guidelines set forth by the Radiation Therapy Oncology Group (RTOG) and utilised recommendations from the International Commission on Radiation Units and Measurements (ICRU) Report 50 for the delineation of target volumes. The planning target volumes (PTV) were determined by adding a margin to the CTV to accommodate potential internal organ motion, patient movement, and possible setup inaccuracies. A 4-mm exclusion from the skin surface was implemented to prevent under-dosage resulting from the build-up effect. Various structure editing tools available in the

treatment planning system, including brush, eraser, crop structure, and interpolation, were employed throughout the contouring process.

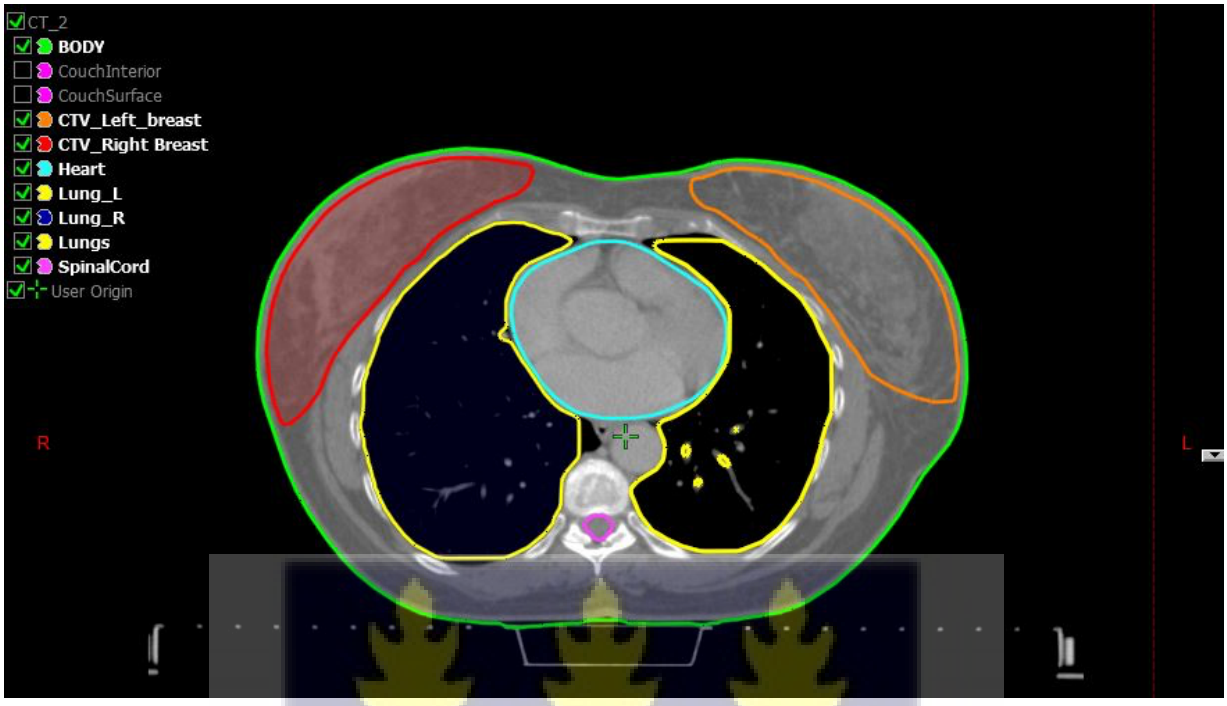

Figure 3.3 Transverse view of a CT image indicating the contoured organs at risk and CTV.

3.9.3 PRESCRIBED DOSE AND FRACTIONATION

In this study, a dose prescription of 50.00 Gy in 25 fractions was used, adhering to the recommendations outlined in RTOG-1305 and ICRU Report 83. While standard whole breast radiotherapy (WBRT) typically involves dose fractionation ranging from 45.00 to 50.00 Gy, delivered in 25 to 28 fractions of 1.80 to 2.00 Gy per fraction, alternative approaches such as hypo-fractionated whole breast radiotherapy (HF-WBRT) have gained traction. Substantial evidence from large-scale randomised trials supports the efficacy of HF-WBRT, which involves delivering doses of 40.05 to 42.56 Gy in 15 to 16 fractions of 2.66 to 2.67 Gy per fraction, as being comparable to standard fractionation for early-stage breast cancer.

However, the standard fractionation method of 50.00 Gy in 25 fractions was used for this research. This choice was driven by the specific focus on both intact breast cases and cases involving radical mastectomy (chest wall).

3.9.4 TREATMENT PLANNING

Table 3.1 Beam parameters to be used for the various plans, respectively.

For each patient, the Eclipse treatment planning system (TPS), with software version 18.0, was employed to create four distinct treatment plans characterised by different beam arrangements and intensities as indicated in Table 3.1.

Machine	Energy	Technique	No.3DRT Beams	No. of Additional Beams	Beam Modifier
LINAC	6MV			2 OPTIMISED BEAMS	MLC
		HYBRID	TWO OPEN TANGENTS	5 OPTIMISED BEAMS	
		IMRT			
		VMAT		2 HALF ARCS	

Each plan was designed to deliver a prescribed dose of 50.00 Gy to the planning target volume (PTV) over 25 fractions. Varian Medical Systems' Unique Performance Linear Accelerator operating at 6 MV, equipped with a multi-leaf collimator (MLC) featuring 120 leaves and a leaf speed of 2.5 cm/s, was used for these plans. In executing three of the techniques, a common isocentre and identical tangential beams were employed, with the exception of the volumetric

modulated arc therapy (VMAT), which utilised arc-based delivery. The treatment planning system applied the triple-A (anisotropic analytic algorithm) for dose calculations, utilising a calculation matrix of 0.25-mm. The generated plans comprised two hybrid plans, one intensity-modulated radiation therapy (IMRT) plan, and one VMAT plan,as shown inFigure 3.4. The hybrid technique is executed in two phases: the initial phase involves a three-dimensional conformal radiation therapy (3DCRT) component, followed by the IMRT phase, which features a dose variation ranging from 80% to 20% between the 3DCRT and IMRT components.

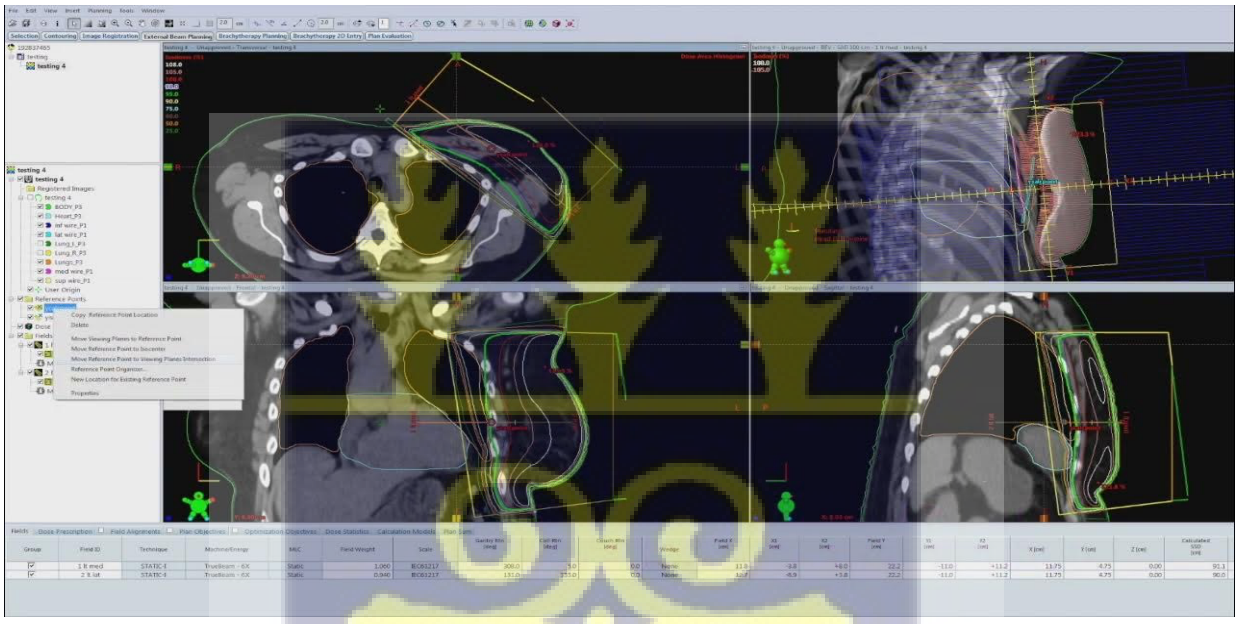

Figure 3.4 Varian Medical System Eclipse treatment planning system (TPS) version 18.0 user interface

3.9.4.1 HYBRID PLANNING TECHNIQUE

Hybrid treatment planning involves a two-step process. The first step is the 3D-CRT step, which involves using a pair of two posterior parallel opposing tangential fields (medial and lateral), with gantry angles selected to ensure that the divergence of the posterior edges is

aligned for both tangential beams. This alignment was crucial to prevent radiation exposure to the contralateral breast while also minimising the irradiation of the ipsilateral lung and heart regions. The gantry angles were optimised to achieve maximal coverage of the planning target volume (PTV). The field setup included the 'flash region' which is a 2-cm anterior extension of the chest to ensure adequate dose coverage to the skin. All subsequent plans were normalised to the same reference point as the hybrid technique to enhance isodose coverage of the breast. Within the 3DCRT framework, 80% of the prescribed dose was calculated at a reference point in accordance with ICRU 50 and 62 standards. Various weightings were applied to ensure a uniform dose distribution throughout the breast tissue. The hybrid approach integrates the advantageous organ-sparing characteristics of 3D-CRT with the dose-optimising capabilities of IMRT, thereby facilitating a uniform dose distribution to the target.

3.9.4.1.1 BASE PLAN

The base plan serves as the foundational treatment strategy, designed to deliver a standardised radiation dose to the entire target volume while minimising exposure to surrounding healthy tissues. For this research, the 3D-CRT (three-dimensional conformal radiation therapy) component is utilised as the base plan.

The base plan in this study was developed by first configuring the tangential fields to deliver an equal dose to the planning target volume (PTV). The dose distribution profile was analysed and adjusted to ensure uniform dose contribution from both tangential fields to the PTV. The target for the mean dose distribution within the PTV was set at 80%. This goal was achieved by fine-tuning the individual beam weights, ensuring that both fields contributed equally without applying normalisation adjustments to the plan. The resulting dose distribution accurately reflects the intended dose correlation for the base plan.

3.9.4.1.2 2-BEAM SETUP IN HYBRID TREATMENT PLANNING (IMRT COMPONENT)

In the second step, two additional beams with parallel opposing posterior ends, sharing the same isocentre as the original of two fields from the base plan, were incorporated into the plan. These beams served as the IMRT (intensity-modulated radiation therapy) or optimised plan component of the hybrid technique. Once the fields were configured and properly aligned, the next step was to optimise the plan.

In the optimisation interface, the base plan was selected as the reference dose, and the original two fields from the base plan were excluded from the optimisation process. This configuration meant that the treatment algorithm would only utilise the two additional fields for optimisation, with these beams contributing the remaining 20% of the dose. Constraints, based on RTOG recommendations, were entered into the optimiser with their respective priorities.

After completing the optimisation process, the plan was calculated. The treatment planning algorithm integrated the dose distribution from both the base plan and the two additional beams. The 3D-CRT component provided a significant portion of the dose using a simpler, less time-consuming method, ensuring broad coverage of the target volume. Meanwhile, the IMRT component refined the dose distribution, addressing the limitations of 3D-CRT by enhancing precision and sparing critical structures through the use of multi-leaf collimators. Figure 3. 5 shows the transverse view of how the radiation beams are arranged for the Hybrid (2 beams) with the individual contoured organs at risk and the 95% isodose line coverage.

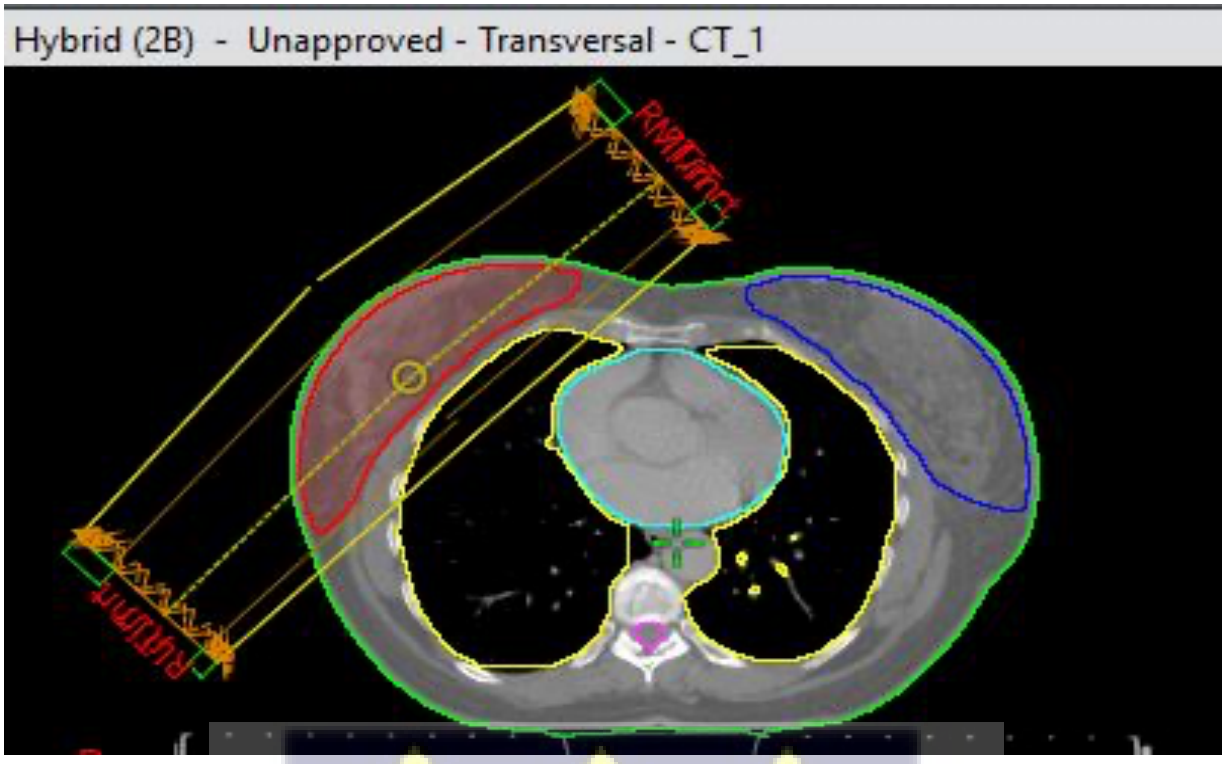

Figure 3.5 Transverse view of the beam arrangement for the Hybrid (2 beams) technique.

3.9.4.1.3 5-BEAM SETUP IN HYBRID TREATMENT PLANNING (IMRT COMPONENT)

Similar to the 2-beam setup, the 5-beam configuration contributed 20% of the prescribed dose. The base plan was first duplicated and renamed as the hybrid plan. Five additional beams were added to the original two medial and lateral tangential beams from the base plan. Among these five beams, there was a replica of the tangential beams, and three other beams were arranged with gantry angles tailored to the side of the breast being treated. For left-sided breast cases, the gantry angles were set at 0°, 45°, and 90°, while for right-sided breast cases, the angles were set at 0°, 315°, and 270°as shown in Figure 3.6. These five beams were used for optimisation, collectively contributing the remaining 20% of the dose.

In the optimisation window, the base plan was selected as the reference dose, and the two original medial and lateral beams were excluded from the optimisation process. This approach ensured that the Treatment Planning System (TPS) algorithm utilised only the five beams for dose modulation, fine-tuning the dose to achieve the 20% contribution. Various tolerance levels and their priorities were input into the optimiser, and adjustments were made during the optimisation process to guide the system in prioritising the modulation of specific organs or structures to meet the desired constraints.

The majority of the dose was delivered by the 3D-CRT component, while the optimiser employed multi-leaf collimators to generate beamlets with varying intensities, further refining the dose distribution to enhance treatment precision and minimise exposure to surrounding healthy tissues.

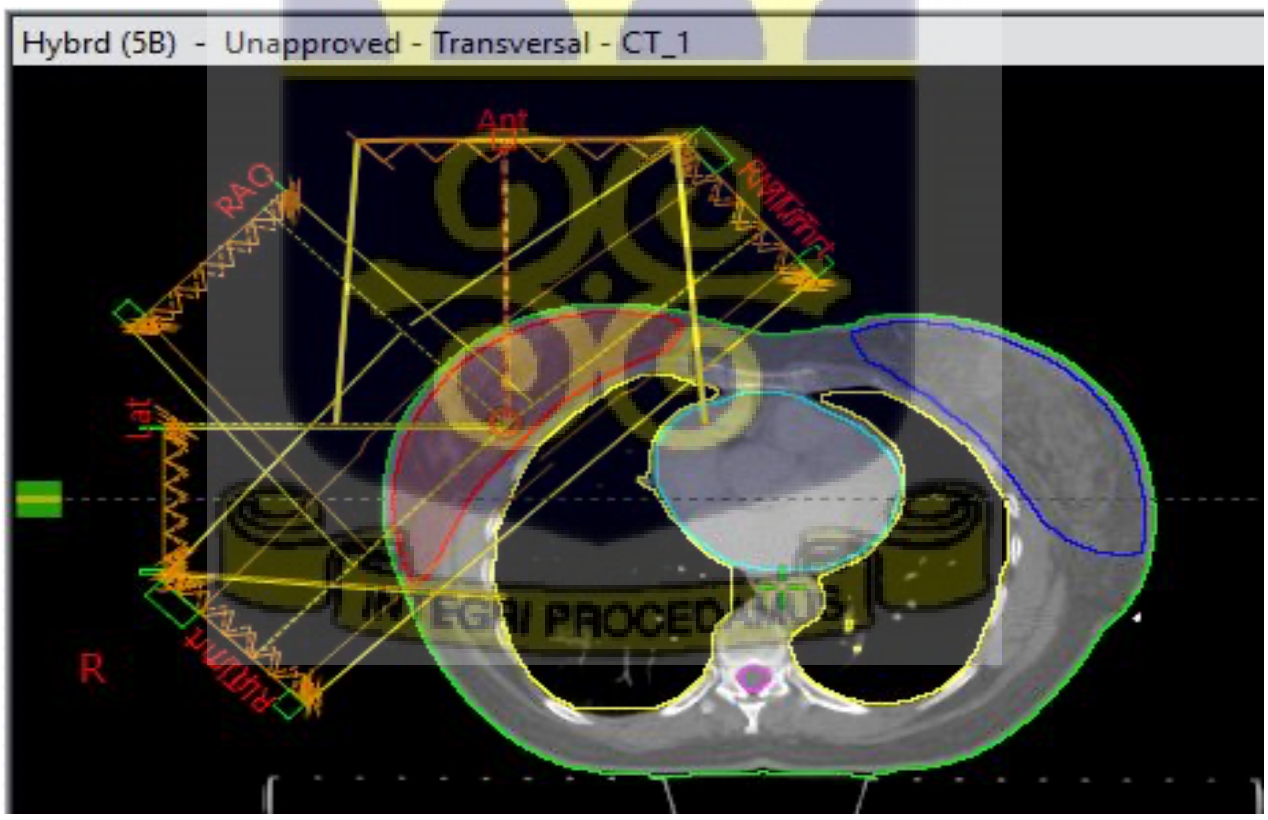

Figure 3.6 Transverse view of the beam arrangement for the Hybrid (5 beams) technique.

3.9.4.2 IMRT (FULL IMRT) TREATMENT PLANNING

The IMRT treatment planning process began by setting up two tangential fields with parallel opposing posterior beams. The gantry angles were carefully selected to align the posterior edges of the tangential beams, minimising the risk of irradiating the contralateral breast and reducing exposure to the ipsilateral lung and heart. The gantry angles were optimised to ensure optimal coverage of the planning target volume (PTV).

Three additional fields were then set up, taking into consideration the side of the breast being treated. The fields were positioned as follows: anterior, left or right anterior oblique, and right or left lateral, corresponding to 0°, 45° or 315°, and 90° or 270° gantry angles, respectively. This field arrangement is shown in Figure 3.7

The Treatment Planning System (TPS) utilised a 120-leaf Millennium multileaf collimator, with a maximum speed of 0.25 cm/s, to achieve intensity variation and ensure uniform dose distribution across the tissues. The plan was optimised within the TPS's optimisation window, adhering to RTOG constraints for both the PTV and organs at risk. Various tolerance levels and their priorities were input into the optimiser, and adjustments were made during the optimisation process to guide the system in prioritising the modulation of specific organs or structures to meet the desired constraints.

Once the optimisation was completed, the plan was calculated. As per the guidelines in ICRU Reports 50 and 62, the plans were normalised to a reference point with 100% mean dose contribution to the target. The anisotropic analytical algorithm was employed for dose calculation, ensuring accurate and precise dose delivery.

Figure 3.7 Transverse view of the beam arrangement for the Full IMRT technique.

3.9.4.3 VMAT TREATMENT PLANNING

The treatment plans for Volumetric Modulated Arc Therapy (VMAT) were developed using two half-arcs sharing the same isocentre to achieve optimal Planning Target Volume (PTV) coverage while minimising the dose to organs at risk (OARs). The starting and ending points of the arcs were carefully optimised: the medial portion was adjusted to avoid passing through the contralateral breast, and the lateral portion was configured to minimise lung involvement. Since two arcs were employed, the endpoint of the first arc became the starting point of the second arc, and vice versa. For example, Arc 1 would begin at a gantry angle of 45 degrees and conclude at 235 degrees, while Arc 2 would start at 235 degrees and end at 45 degrees. The direction of gantry movement, whether clockwise or counterclockwise, was determined by the side of the breast being treated. Figure 3.8 shows the 2 half-arc arrangement for a right-sided breast being treated.

Following the arc setup, the optimisation process commenced. The VMAT optimisation interface differs slightly from that of IMRT. Initially, constraints and priorities for the PTV were entered into the system. The optimisation process was then initiated, after which the constraints and priorities for the OARs were input. Adjustments to the priorities and constraints were made during the optimisation process to guide the system in prioritising the modulation of specific organs or structures to meet the desired constraints. The treatment planning system (TPS) modulated the multi-leaf collimators to optimise the dose distribution across both the target and the OARs. Upon completion of the optimisation process, the system automatically closed the optimisation window and proceeded with the dose calculation.

In accordance with ICRU Report 83 guidelines, the plans were normalised to a reference point with a 100% mean dose contribution to the target,as shown in Figure 3.8. This approach ensures that the PTV receives the intended dose while adhering to the established safety limits for surrounding healthy tissues.

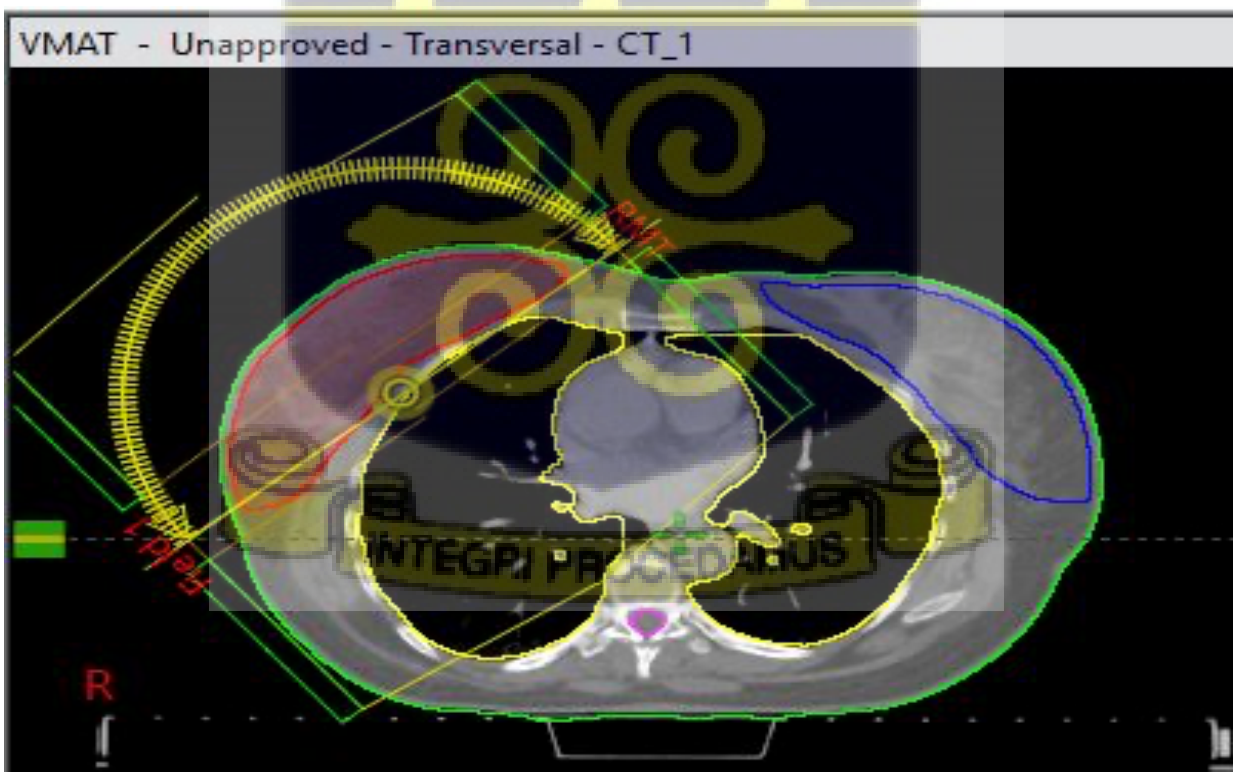

Figure 3.8 Transverse view of the arc arrangement for the VMAT technique.

3.9.5 PLAN AND DATA ANALYSIS

The dose volume histogram was used to quantitatively evaluate all four treatment plans as shown in Figure 3.9 and the analysis in Table 3.2. The structures evaluated included the PTV, contralateral breast, the ipsilateral lung, and the heart. The parameters of the PTV that were evaluated included the maximum and minimum dose, D95% (the dose to 95% of the volume), D98% (the dose to 98% of the volume), and D2% (the dose to 2% of the volume) were compared between the 2 Hybrid, the IMRT and VMAT for each individual. The Conformity Index was calculated using equation (2). The CI ranges from 0 to 1, and 1 suggests the best or optimal value or the most conformed plan. Using the ICRU 83 report as a guide, the homogeneous index (HI) was also calculated using equation (1).

The optimal value for HI is approximately zero. When the values of HI decrease, a better dose homogeneity is achieved. The parameters evaluated for the OAR's included: D15 for the contralateral breast, D20 and D40 for the heart, D30, and D45 for the ipsilateral Lung and D25 and D20 for combined lungs. The average monitor units per 2 Gy of each plan were also evaluated to assess the treatment delivery time for the various techniques and as well as to estimate the planning complexity of all four techniques.

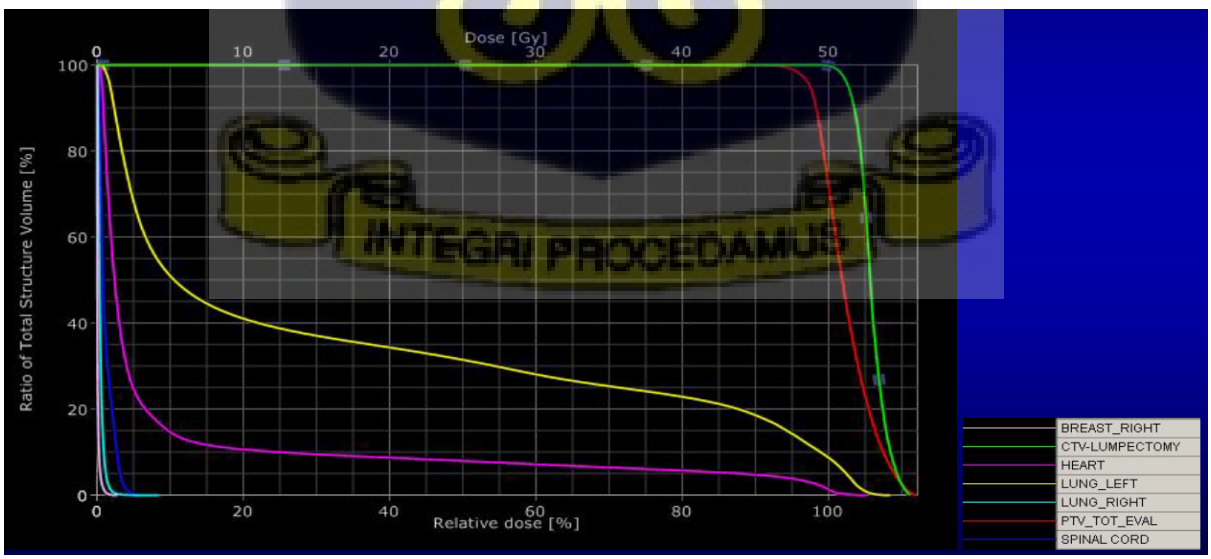

Figure 3.9 Dose volume histogram (DVH)

Table 3.2 Dose-volume constraints used to analyze the various plans.

Dose Volume Constraints		
Protocol RTOG Catton *et al*., (2017)	Structure	Constraints
	PTV	D95 ≥ 95%, Dmax ≤ 107%
	Contralateral Breast	D15% ≤ 5 Gy
	Ipsilateral Lung	D45% ≤ 20.0Gy, D35% ≤ 30.0Gy
	Heart	D40% ≤ 5.0Gy, D20% ≤ 20Gy
	Combined Lungs	D25% ≤ 20.0Gy, D20% ≤ 30.0Gy

3.9.6 DATA COLLECTION TOOLS

The data collection tools that were used included an Eclipse TPS version 13.6 and a self-designed data collection sheet (using Microsoft Excel 2019 version 2208).

3.9.7 STATISTICAL ANALYSIS

Inferential and descriptive analysis were performed on the data acquired from the treatment planning system using Microsoft Excel 2019 version 2208. The descriptive analysis included, means for the various dosimetric parameters together with their standard deviations and range. The inferential analysis included ANOVA test to determine if there were statistically

significant differences between the means. The findings were presented through tables, histograms and a clustered chart. A significance level of 0.05 was used for the ANOVA test to compare the P-value of the means of the four plans using Microsoft Excel 2019 version 2208.

3.10 ETHICAL CONSIDERATIONS

The Ethical and Protocol Review Committee of the University of Ghana approved the study following a formal request. Furthermore, authorisation was secured from the management of the National Radiotherapy Oncology and Nuclear Medicine Centre (NRONMC) at Korle Bu Teaching Hospital (KBTH) to utilise retrospective images for the development of the plans necessary for this research. To maintain confidentiality and anonymity, patient identifiers were substituted with a three-digit code. In addition, data security protocols were established, which included password protection and access restrictions limited to supervisors and me, the researcher.

CHAPTER FOUR

RESULTS AND DISCUSSION

4. 0 INTRODUCTION

In this section, the dosimetric indices of the four treatment modalities for breast irradiation are discussed and compared to ascertain their statistical significance. Common notations and parameters in the literature that are used to evaluate treatment plan quality such as D2%, D15%, D20%, D25%, D35%, D45%, D50%, D95%, and D98% represent the absolute doses received by 2%, 15%, 20%, 25%, 35%, 45%, 50%, and 98% volume of a delineated structure during the organ segmentation process of the treatment planning. The parameters evaluated for the PTV are D2%, D50%, D95%, and D98% while D15%, D205, D25%, D35%, and D45% are parameters used to evaluate the organs at risk. Simultaneously, the total MU for each plan for the same dose prescription (2 Gy) was evaluated. The MUs were compared to ascertain differences in treatment durations and to assess the plan's complexity. The raw data for these evaluated parameters were indicated in Appendix B.

4.1 EVALUATION OF PTV INDICES FOR CHEST WALL

4.1.1 HOMOGENEITY INDEX EVALUATION

The homogeneity indices (HI) for each of the chest-wall breast cancer cases were calculated using the raw data from Appendix B and substituted into equation (3.1). The HI values were plotted for all of the techniques under comparison as indicated in Figure 4.1. The lowest HI value was observed in Hybrid (5 Beams) (0.061 ± 0.008), indicating superior dose homogeneity. VMAT had the highest HI value (0.105 ± 0.014) with a p-value of 1.105×10^{-20}, suggesting significant dose variability. The mean HI values for IMRT and Hybrid (2 Beams) were 0.071 ± 0.017 and 0.090 ± 0.022, respectively as shown in Table 4.1be. Figure 4.2 shows

the plot of the HI values for all chest-wall cases. The solid-coloured bars indicate the mean for the HI values, and the error bars indicate the standard deviations for each technique.

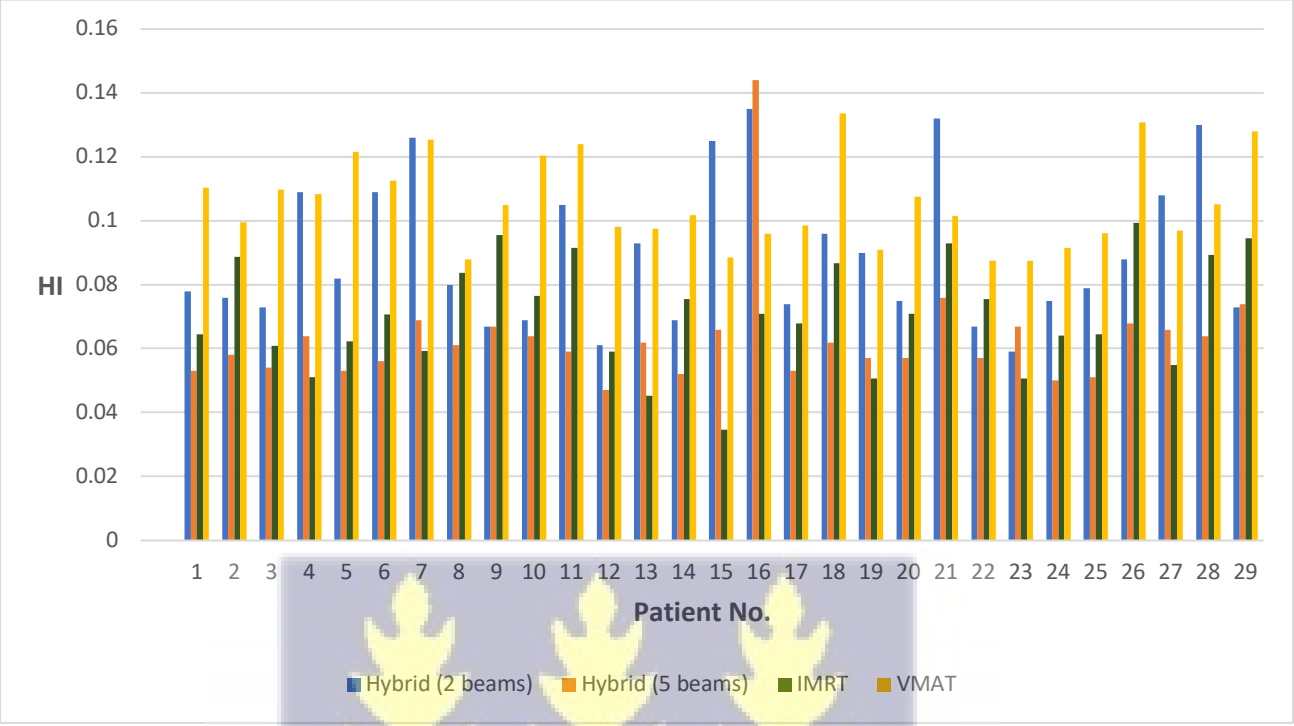

Figure 4.1 Histograms showing the homogeneity indices against the patient ID for all chest-wall cases

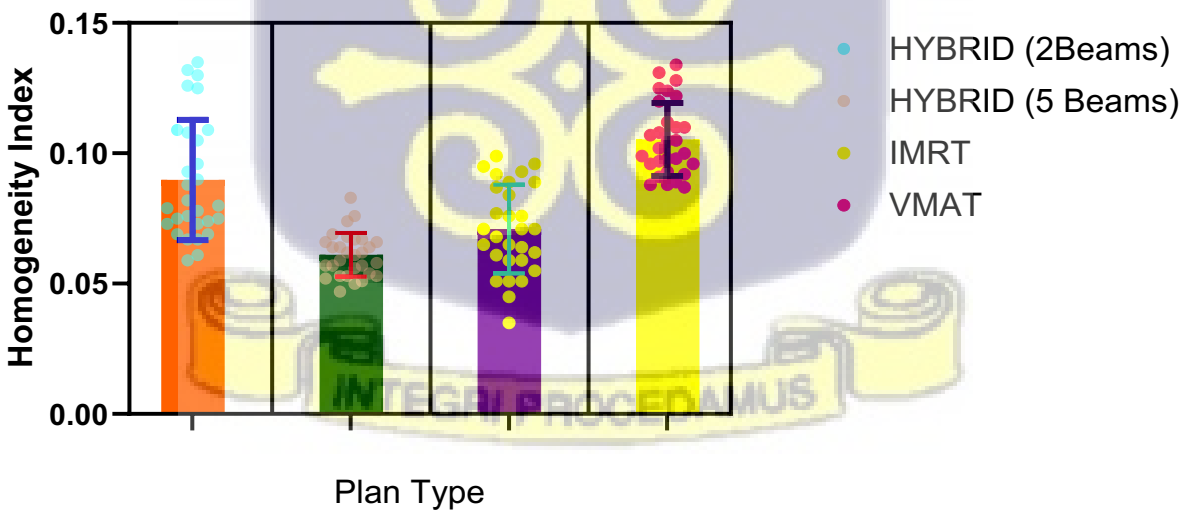

Figure 4.2 Homogeneity indices with their means and standard deviations of PTV for all chest-wall cases.

The ICRU report 83 establishes the optimal value for HI to be 0, and this value increases as the plan becomes less uniform. Values closer to 0 are more homogeneous than values that are further away from 0 (ICRU,2010). Thus, values closer to the ideal value indicate a more homogeneous distribution of dose in the target. From the study results, Hybrid (5 Beams) had its mean HI value closest to 0 (0.061 ± 0.008), with hybrid (2 Beams), IMRT, and VMAT in increasing order of HI values, that is 0.071 ± 0.017, 0.090 ± 0.022, and 0.105 ± 0.014, respectively.

The superior homogeneity observed with the Hybrid (5 Beams) technique can be attributed to the use of multiple, non-overlapping fixed beams, which allow for more controlled and uniform dose distribution. The non-opposing beam angles help avoid overlapping high-dose regions, minimising hotspots and improving dose uniformity within the PTV. The distribution of the dose across these multiple angles further smooths out high-dose regions, resulting in better overall homogeneity. The superior homogeneity observed with the Hybrid (5 Beams) technique can be attributed to the use of multiple and non-overlapping fixed beams that allow for more controlled and uniform dose distribution. The dose distribution across these multiple angles helps to smooth out high-dose regions, thereby reducing hotspots and improving dose uniformity within the PTV. Literature supports this finding, noting that using multiple beams can mitigate the effect of tissue heterogeneity and reduce dose gradients within the target volume (Awan, *et al*., 2012).

On the other hand, VMAT's poor homogeneity is a consequence of its delivery technique. VMAT utilises continuous modulation of beam intensity and rotation around the patient, which, while excellent for conformality, can lead to increased dose heterogeneity within the target. The dynamic nature of VMAT, with continuous changes in gantry speed, dose rate, and

MLC positions, can result in complex dose distributions with higher variability (Zhao *et al*., 2016). When VMAT is compared with IMRT, IMRT has lower or better dose homogeneity than VMAT. However, VMAT requires less delivery time and monitor units than IMRT and Hybrid (5 beams). A study by Mishra *et al*. (2023) reported that VMAT demonstrated better dose homogeneity than IMRT, which is contradictory to the findings from this study.

In the study conducted by Nakamura *et al*. (2014), the authors aimed to evaluate the target coverage, homogeneity, and robustness of dose distributions in relation to geometrical uncertainties present in four different whole breast radiotherapy techniques. They found that intensity-modulated radiation therapy (IMRT) exhibited significant geometrical uncertainties due to setup errors and target motion, which diminishes its advantages for breast cancer treatment. To address these issues, the authors suggested that integrating two opposed tangential open beams with IMRT could create a hybrid IMRT plan that mitigates the geometrical uncertainties associated with IMRT. Their findings supported this hypothesis, demonstrating that hybrid IMRT exhibited greater robustness against uncertainties compared to conventional IMRT, while also maintaining high plan quality.

Liu *et al*. (2020), conducted a dosimetric comparison of intensity-modulated radiotherapy (IMRT), volumetric modulated arc therapy (VMAT), and hybrid three-dimensional conformal radiotherapy/intensity-modulated radiotherapy techniques for the treatment of right breast cancer. Their findings indicated that the hybrid IMRT exhibited superior dose homogeneity, while VMAT demonstrated the highest dose conformity. These results align with the current study's findings and are consistent with existing literature on the subject.

4..1.2 CONFORMITY INDEX EVALUATION

The conformity indices for all chest-wall cases were plotted for all the treatment plans under comparison as indicated in Figure 4.3. It was observed that in all chest-wall cases, VMAT had

the best CI value with IMRT, Hybrid (5 Beams) and Hybrid (2 Beams) in increasing order of CI value. The results from the plans showed two outliers for the Hybrid (2 beams) plan, as indicated in Figure 4.4. VMAT is the most conformed plan followed by IMRT, Hybrid (5 Beams) and Hybrid (2 Beams), respectively. The mean CI values for VMAT, IMRT, Hybrid (5 Beams) and Hybrid (2 Beams) were 1.066 ± 0.040, 1.195 ± 0.059, 1.325 ± 0.099, and 1.528 ± 0.19, respectively as shown in Table 4.1. Further analysis showed less variance with VMAT and IMRT, while both Hybrids (5 beams and 2 Beams) showed significant variance. There were also significant differences between the CI values of the various plans when compared. The P-values were 2.9347×10^{-13} for IMRT, 2.5832×10^{-15} for Hybrid (5 Beams), and 1.8553×10^{-17} for Hybrid (2 Beams) as indicated in Table 4.1.

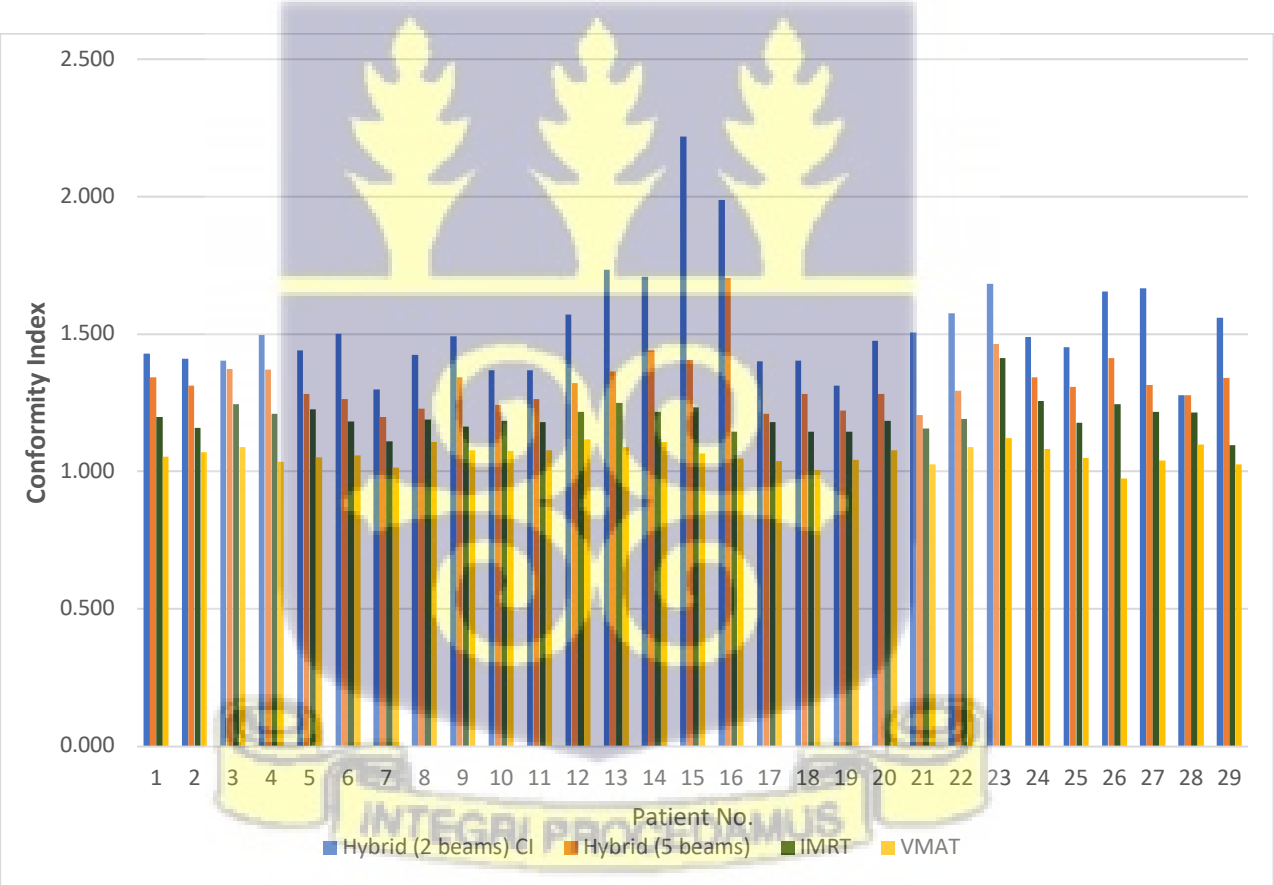

Figure 4.3 Histograms showing the conformity indices against the patient ID for all chest-wall cases.

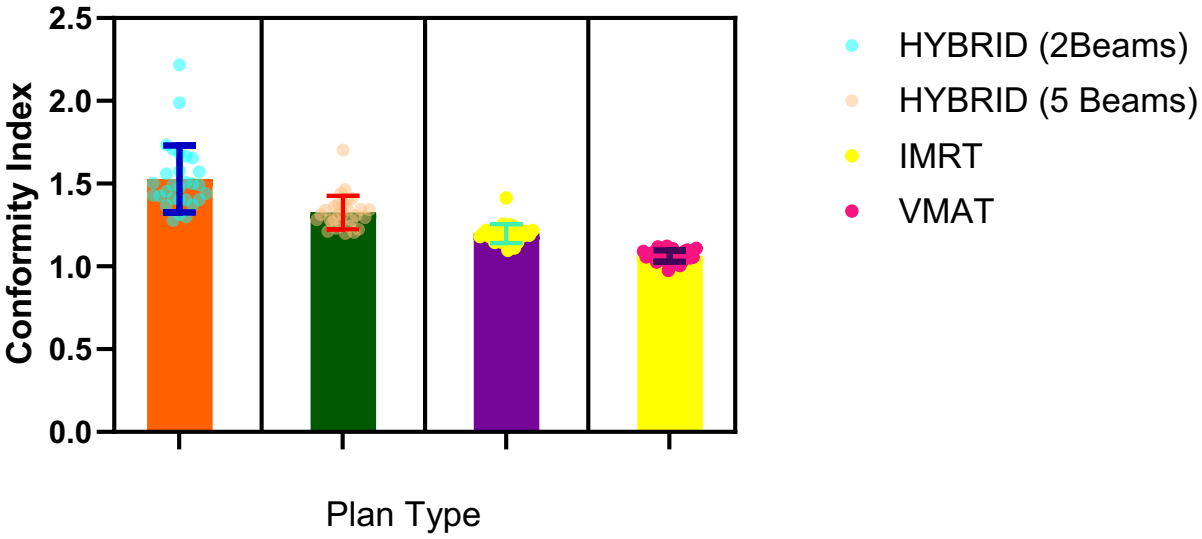

Figure 4.4 Conformity indices with their means and standard deviations of PTV for all chest-wall cases.

Figures 4.5 and 4.6 show how the dose is distributed within the PTV. The various isodose levels in both colour-wash and isodose lines for the axial and coronal view are illustrated to indicate conformity between the four techniques.

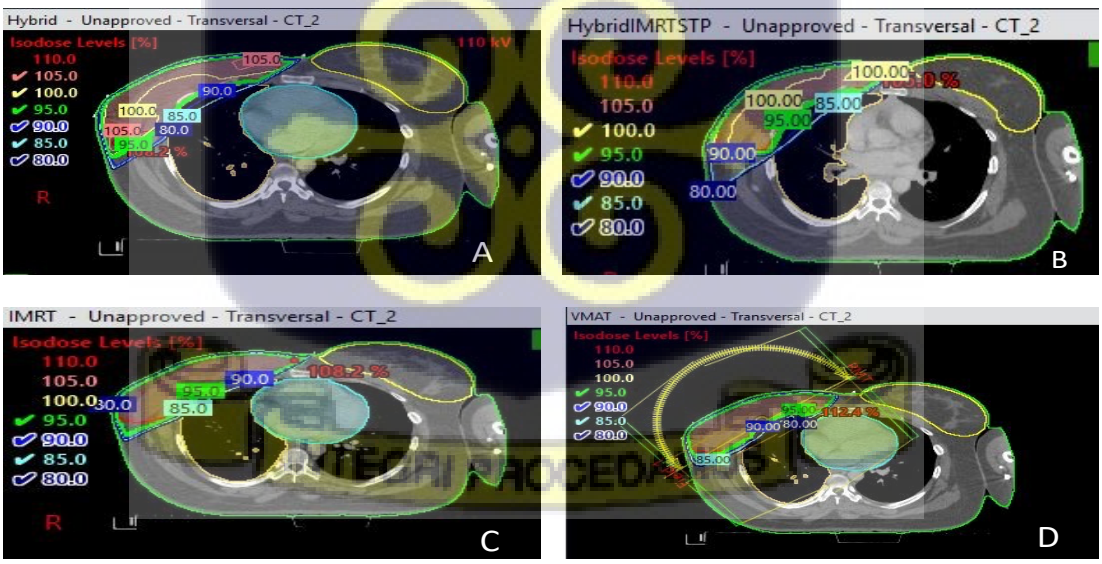

Figure 4.5 Axial CT images with contoured structures and dose distribution for the four techniques; A. Hybrid (2 beams), B. Hybrid (5 Beams), C. IMRT, D. VMAT

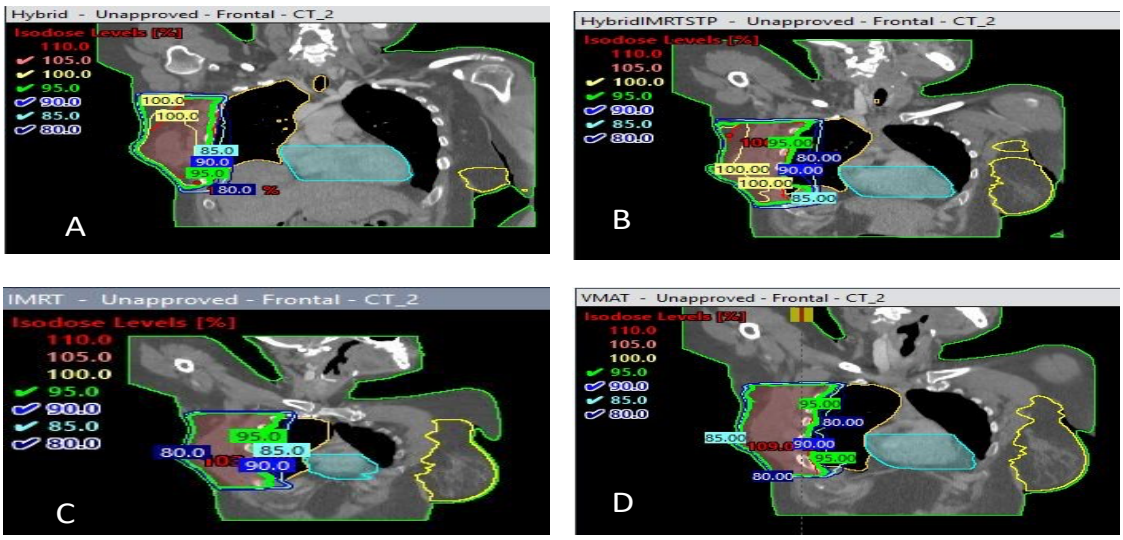

Figure 4.6 Coronal CT images with contoured structures and dose distribution for the four techniques; A. Hybrid (2 beams), B. Hybrid (5 Beams), C. IMRT, and D. VMAT.

According to the standards set by the International Commission on Radiation Units and Measurements (ICRU) Report 83, the optimal CI value is 1. A CI value of 1 implies perfect conformity, meaning the radiation dose fully encompasses the target volume without extending into adjacent healthy tissues.

In this study, the analysis revealed that all techniques resulted in CI values greater than 1, indicating that while the target volumes were adequately covered, some degree of irradiation extended into surrounding normal tissues. Among the evaluated techniques, the Hybrid (2 Beams) plan exhibited the highest mean CI. This suggests that, although the Hybrid (2 Beams) approach achieved adequate target coverage, it also resulted in more significant irradiation of surrounding tissues than the other techniques. This is consistent with the findings of Xu *et al.* (2015), who observed that simpler techniques, such as 3D-CRT-based hybrids, tend to have higher CI values due to less sophisticated dose modulation capabilities. The Hybrid (5 Beams) technique demonstrated an improved CI of 1.325 ± 0.099. The addition of three more beams in this approach appears to have enhanced dose conformity, reducing unnecessary exposure to

normal tissues. This result aligns with the study by Yang *et al.* (2016), which highlighted the benefits of increasing the number of beams in hybrid plans to improve dose distribution and conformality. The IMRT technique, with a CI of 1.198 ± 0.057, showed further improvement, indicating that the more advanced modulation of beam intensity in IMRT allowed for better conformation to the target volume. However, it is the VMAT technique that achieved the best conformity, with a mean CI of 1.063 ± 0.034. The superior performance of VMAT is supported by the findings of various studies, including those by De Rose *et al.*, (2016) and Zhao *et al.*, (2015), which demonstrates that VMAT's dynamic delivery of dose across a wide range of gantry angles enables highly conformal plans with minimal exposure to surrounding tissues.

A CI value greater than 1, while ensuring full coverage of the target volume, also suggests the potential for overtreatment where normal tissues receive higher doses than necessary. This raises concerns about increased toxicity and adverse effects on healthy tissues, particularly in organs at risk (OARs) such as the lungs and heart in breast cancer treatments. According to the Radiation Therapy Oncology Group (RTOG) protocol, as outlined in ICRU Report 62, a CI within the range of $1 \leq CI \leq 2$ is considered acceptable, as it indicates adequate target coverage with a reasonable level of normal tissue irradiation. Values within the range of $1 < CI \leq 1.5$ are particularly desirable, as they suggest a small, controlled extension of the dose into surrounding tissues, which is often necessary to ensure full coverage of the target volume while minimising the risk of missing any part of the tumour (Shamsi *et al.*, 2017)

In this study, all CI values for the four techniques fell within the $1 < CI \leq 1.5$ range, indicating that all plans agreed with the RTOG guidelines. The results suggest that while the Hybrid (2 Beams) technique may result in more extensive irradiation of healthy tissues, the Hybrid (5 Beams) and IMRT techniques offer better conformity. However, VMAT stands out as the most conformal technique, offering the best balance between target coverage and sparing of normal tissues.

Table 4.1 Summary of mean PTV dose volume histogram (DVH) parameters for four treatment plans (Chest Wall).

Structures	Hybrid (2 Beams)	Hybrid (5 Beams)	IMRT	VMAT	*P-Value*		
PTV					Hybrid (5beams) vs hybrid (2beams)	Hybrid (5beams) vs IMRT	Hybrid (5beams) vs VMAT
D2 (Gy)	52.37 ± 0.802	51.66 ± 0.521	51.91 ± 0.513	52.38 ± .354	0.0003	0.0759	1.8489×10^{-7}
D50 (Gy)	49.99 ± 0.114	49.98 ± 0.093	49.96 ± .097	50.05 ± 0.061	0.7590	0.3822	0.0007
D98 (Gy)	47.88 ± 0.404	48.51 ±0.368	48.38 ± 0.443	47.09 ± 0.438	1.1949×10^{-7}	0.2485	2.0946×10^{-18}
HI	0.090 ± 0.022	0.061 ± 0.008	0.071 ± 0.017	0.105 ± 0.013	5.083×10^{-8}	0.0080	1.105×10^{-20}
					VMAT vs Hybrid (2 beams)	VMAT vs Hybrid (5 beams)	VMAT Vs IMRT
CI	1.528 ± 0.198	1.325 ± 0.099	1.198 ± 0.057	1.063 ± 0.034	1.8553×10^{-17}	2.9347×10^{-13}	2.5832×10^{-15}
					Hybrid (2 beams) vs Hybrid (5 beams)	Hybrid (2 beams) vs IMRT	Hybrid (2 beams) vs VMAT
MU	388.3 ± 20.2	729.0 ± 80.7	949.1 ± 81.2	434.6 ± 43.9	6.5294×10^{-29}	2.9550×10^{-38}	4.5313×10^{-06}

4.2 DOSE ANALYSIS OF OARS (CHEST WALLS)

4.2.1 Dose Analysis of the Ipsilateral Lung

As presented in Table 4.2, the dose parameters used in evaluating the ipsilateral lung for the chest-wall cases were D35% and D45%. The mean dose to the D45% volume of the ipsilateral lung was recorded as 3.013 Gy ± 0.875 for the Hybrid (2 Beams) technique, 8.281 Gy ± 1.532 for Hybrid (5 Beams), 10.349 Gy ± 1.851 for IMRT, and 12.528 Gy ± 2.220 for VMAT. Similarly, the D35% volume exhibited mean doses of 4.891 Gy ± 1.962, 11.207 Gy ± 1.994, 13.260 Gy ± 1.965, and 17.145 Gy ± 2.329 for Hybrid (2 Beams), Hybrid (5 Beams), IMRT, and VMAT, respectively. Figures 4.9 and 4.10 illustrate the mean doses of the parameters being analysed for the ipsilateral lung for each planning technique with their respective standard deviations. The red horizontal line in Figures 4.9 and 4.10 indicates the dose tolerance levels per each parameter analysed.

The findings as shown in Figure 4.7, 4.8, and 4.9, indicate that VMAT resulted in the highest dose to the ipsilateral lung, followed by IMRT, Hybrid (5 Beams), and Hybrid (2 Beams). These results align with previous studies that highlight the increased dose to the ipsilateral lung with advanced techniques such as VMAT, which, while offering superior target coverage and conformity, also tend to involve more complex beam arrangements that can inadvertently increase the dose to nearby healthy tissues, including the ipsilateral lung. For instance, Darby *et al*. (2013) noted that the application of VMAT in chest wall irradiation correlates with elevated lung doses due to the necessity of covering extensive chest wall volumes and the ribs.

Higher doses to the ipsilateral lung increase the risk of radiation pneumonitis (RP), a condition characterised by inflammation and fibrosis of lung tissue within the irradiated volume. Liu *et al*. (2020) reported that the risk of developing RP increases within six months of treatment as the volume of lungs receiving 20 Gy or more (V20Gy) exceeds 20%. Given that both VMAT and IMRT delivered substantially higher doses to the ipsilateral lung compared to the hybrid

techniques, these advanced techniques may pose a greater risk for lung toxicity, although all four techniques adhered to their desired dose constraints

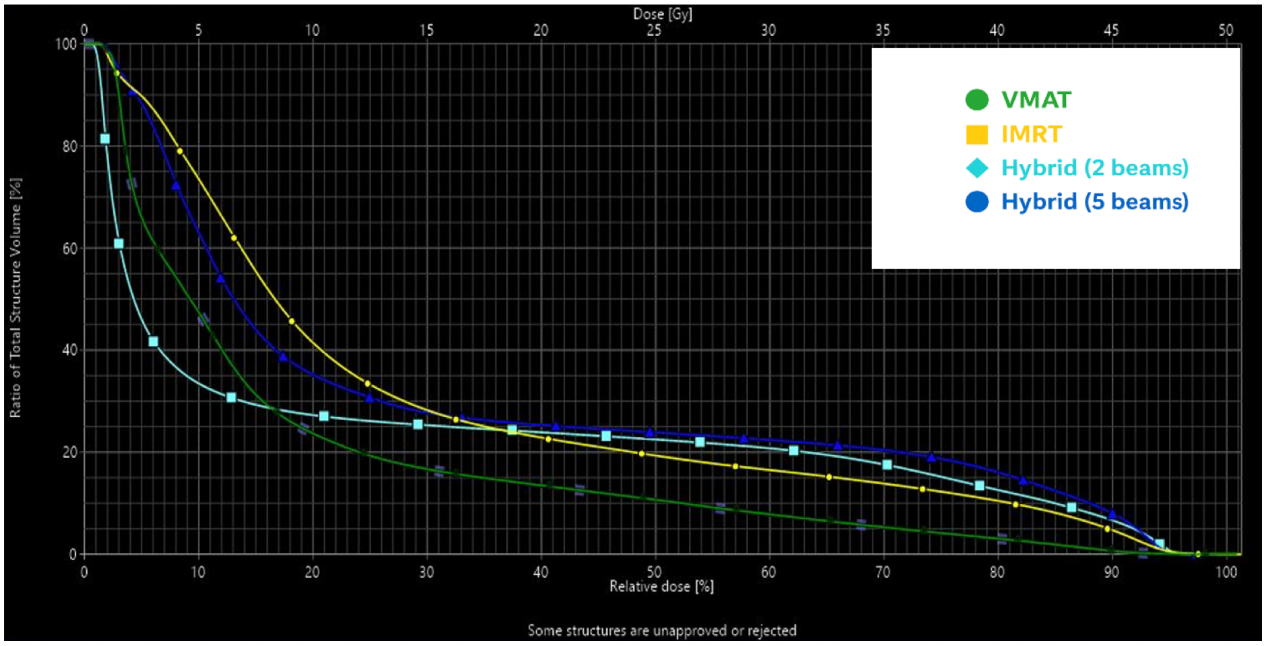

Figure 4.7 Dose volume histogram of the ipsilateral lung for all four techniques for a single patient (chest-wall).

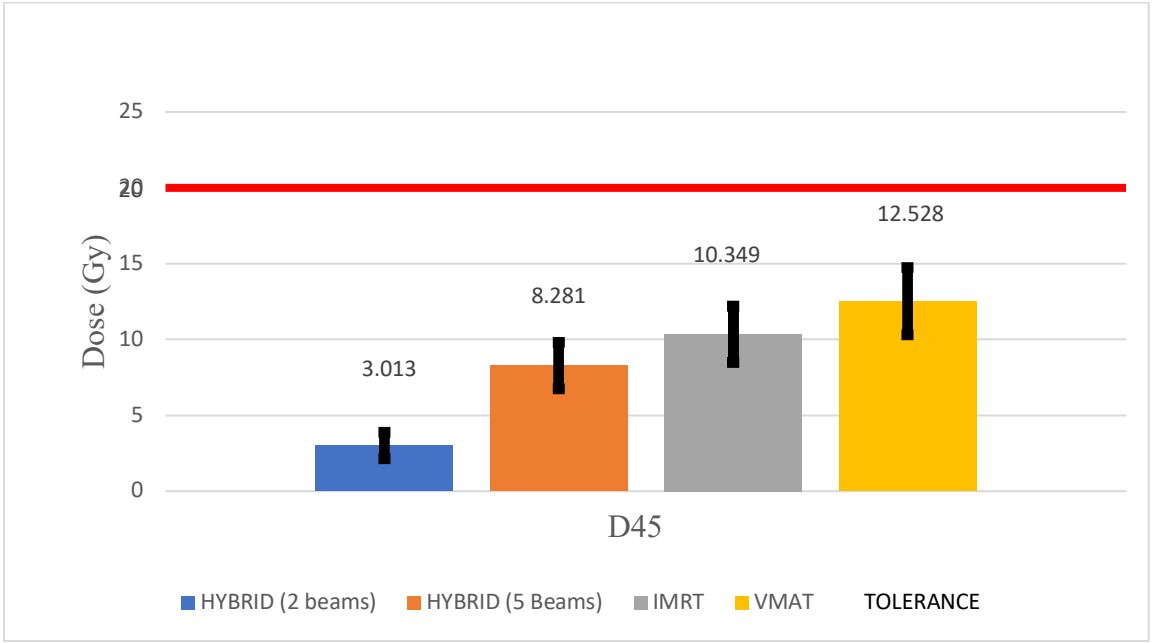

Figure 4.8 Mean doses to 45 % relative volume of the ipsilateral lung for chest-wall cases.

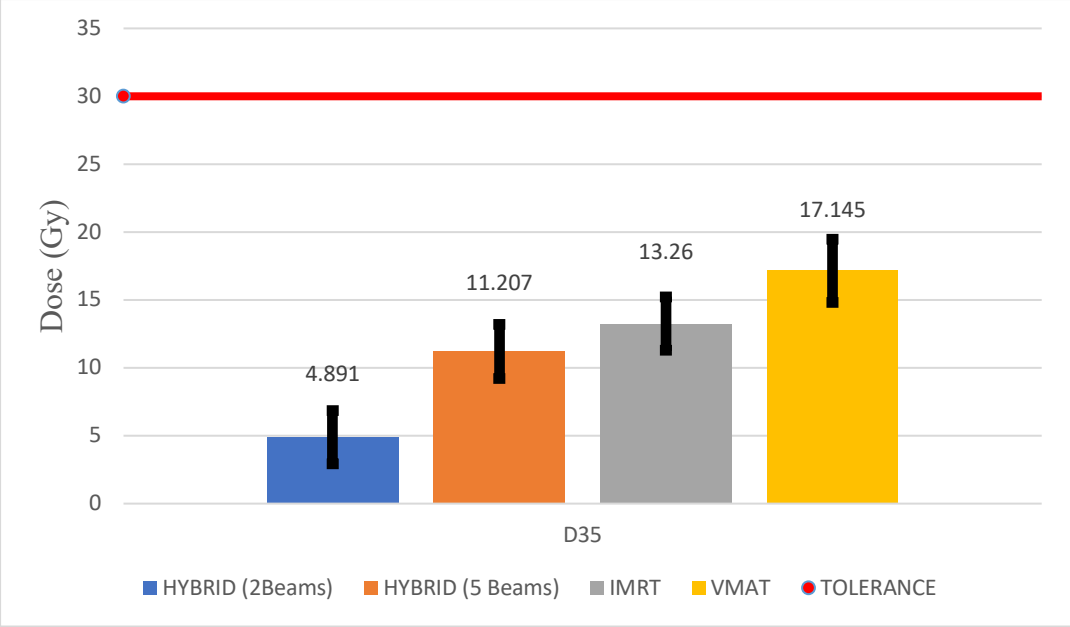

Figure 4.9 Mean doses to 35 % relative volume of the ipsilateral lung for chest-wall cases.

4.2.2 Dose Analysis of the Combined Lungs

The analysis of the combined lungs was conducted utilising dose parameters D20% and D25%. The results indicated that the mean dose to the D25% volume of the combined lungs was 2.464 Gy ± 0.734 for Hybrid (2 Beams), 7.415 Gy ± 1.729 for Hybrid (5 Beams), 9.911 Gy ± 1.565 for IMRT, and 12.144 Gy ± 2.076 for VMAT. In terms of the D20% volume, the mean doses were 3.975 Gy ± 1.991, 9.725 Gy ± 2.055, 12.216 Gy ± 1.575, and 14.719 Gy ± 2.973 for Hybrid (2 Beams), Hybrid (5 Beams), IMRT, and VMAT, respectively, as shown in Figures 4.10, 4.11 and 4.12. The dose tolerance levels are indicated in a red horizontal line in both instances.

Similar to the ipsilateral lung, the VMAT technique resulted in the highest dose to the combined lungs, followed by IMRT, Hybrid (5 Beams), and Hybrid (2 Beams). This outcome is particularly noteworthy in chest wall irradiation, where the contralateral lung is at risk of incidental radiation exposure, leading to potential long-term complications such as radiation-induced lung injury. This was also reported by Liu *et al*. (2020). The increased dose to the

combined lungs observed with VMAT and IMRT can be attributed to the wider arc and multiple beam angles used in these techniques, which, while enhancing dose conformity to the target, can inadvertently increase dose spillage into adjacent normal tissues.

The clinical significance of these findings cannot be overstated. While the contralateral lung is generally not the primary focus of radiation treatment in chest wall cases, unintentional exposure to high doses can lead to serious complications. Studies, such as those by (Alsaihaty *et al*. (2024), have shown that advanced techniques like VMAT and IMRT, despite their advantages in target coverage, may compromise the safety of the contralateral lung by delivering higher doses than hybrid techniques. This suggests that for patients with significant comorbidities or those at higher risk for lung complications, hybrid techniques may offer a safer alternative by limiting dose exposure to the contralateral lung.

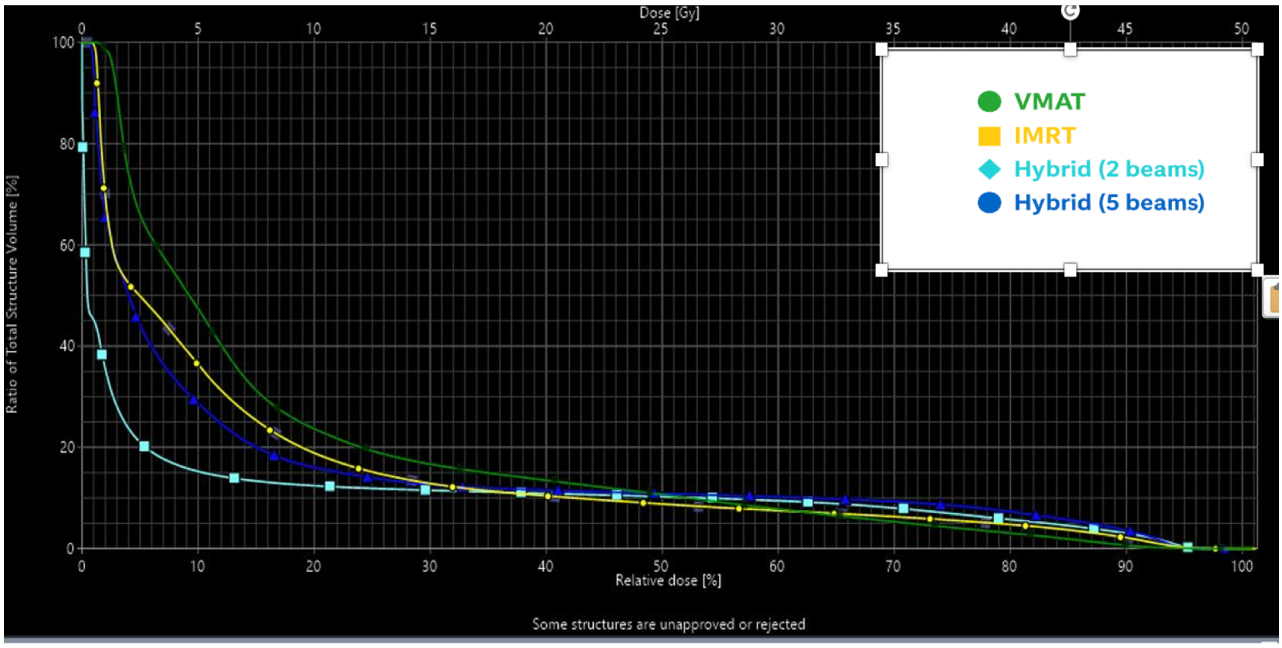

Figure 4.10 Dose volume histogram of the combined lungs for all four techniques for a single patient (chest-wall).

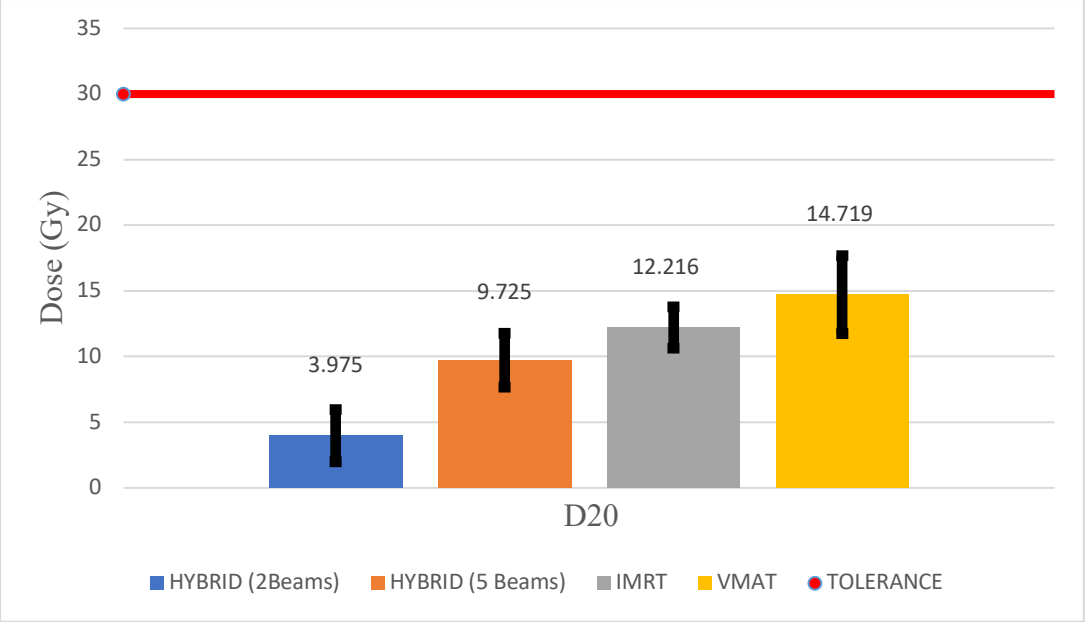

Figure 4.11 Mean doses to 20 % relative volume of the combined lungs (chest-wall cases).

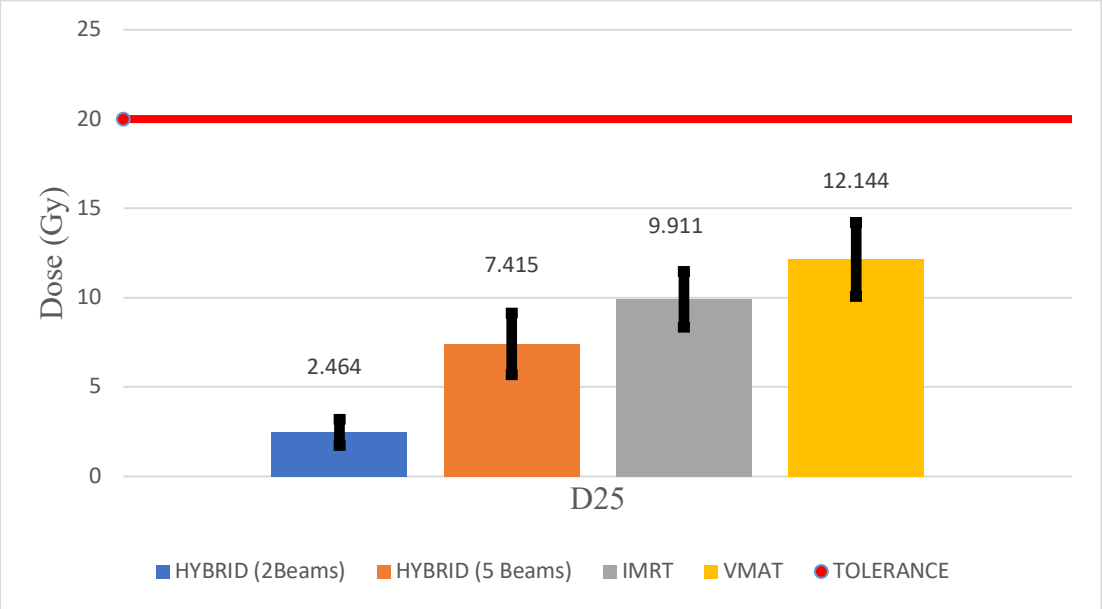

Figure 4.12 Mean doses to 25 % relative volume of the combined lungs (chest-wall cases).

4.2.3 Dose Analysis of the Heart

The heart is a critical organ at risk (OAR) in chest wall irradiation. The mean dose to the D40% volume of the heart was 1.083 Gy ± 0.557 for Hybrid (2 Beams), 2.389 Gy ± 0.599 for Hybrid (5 Beams), 2.705 Gy ± 0.552 for IMRT, and 3.616 Gy ± 0.487 for VMAT. For the D20% volume, the mean doses were 2.578 Gy ± 2.385, 5.139 Gy ± 2.846, 6.162 Gy ± 2.960, and 11.127 Gy ± 3.672 for Hybrid (2 Beams), Hybrid (5 Beams), IMRT, and VMAT, respectively.

The results as shown in Figures 4.13, 4.14 and 4.15 indicate that the Hybrid (2 Beams) technique provided the most significant sparing of the heart, followed by Hybrid (5 Beams), IMRT, and VMAT. The higher doses associated with VMAT and IMRT, as compared to hybrid techniques, raise concerns about the long-term risk of cardiac complications. The findings by Darby *et al*. (2013) underscore the increased risk of cardiovascular disease with higher heart doses, particularly in patients with pre-existing heart conditions. Additionally, the literature suggests that doses to the heart should be minimised to reduce the risk of radiation-induced heart disease, which can manifest years after treatment. Abo-Madyan *et al*. (2014), Calculated the risk of second cancers after radiotherapy in a clinical study using predictive models and found out that, the risk of secondary cancers is higher in VMAT and IMRT than it is in 3DCRT. They recommended the use of a hybrid technique as it provides dosimetric and clinical benefits while having less dose spillage. There is a chance of developing pericarditis when the heart is irradiated but it rarely progresses in a short duration (Darby *et al*., 2013). In the treatment of breast cancer, where some patients have a long-term follow-up. It was found that, with a mean heart dose of 4.9 Gy, the risk of developing cardiovascular disease increases to 7.4% for each 1 Gy additional dose (Wei *et al*., 2008).

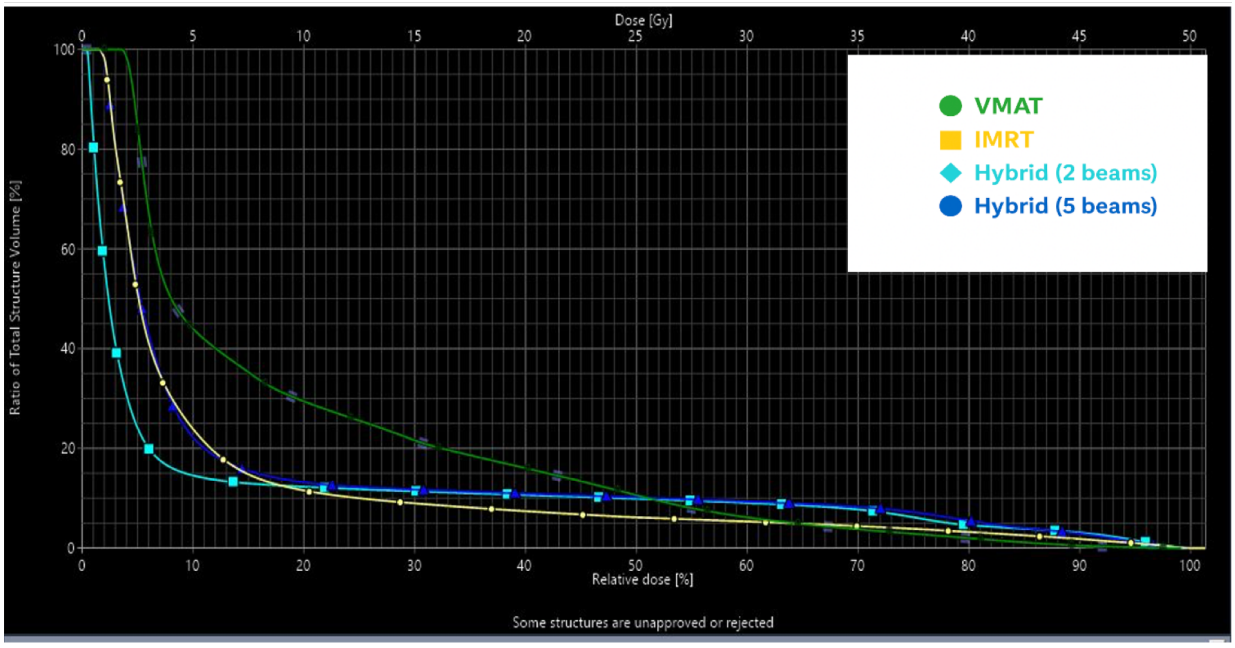

Figure 4.13 Dose volume histogram of the Heart for all four techniques for a single patient (chest-wall).

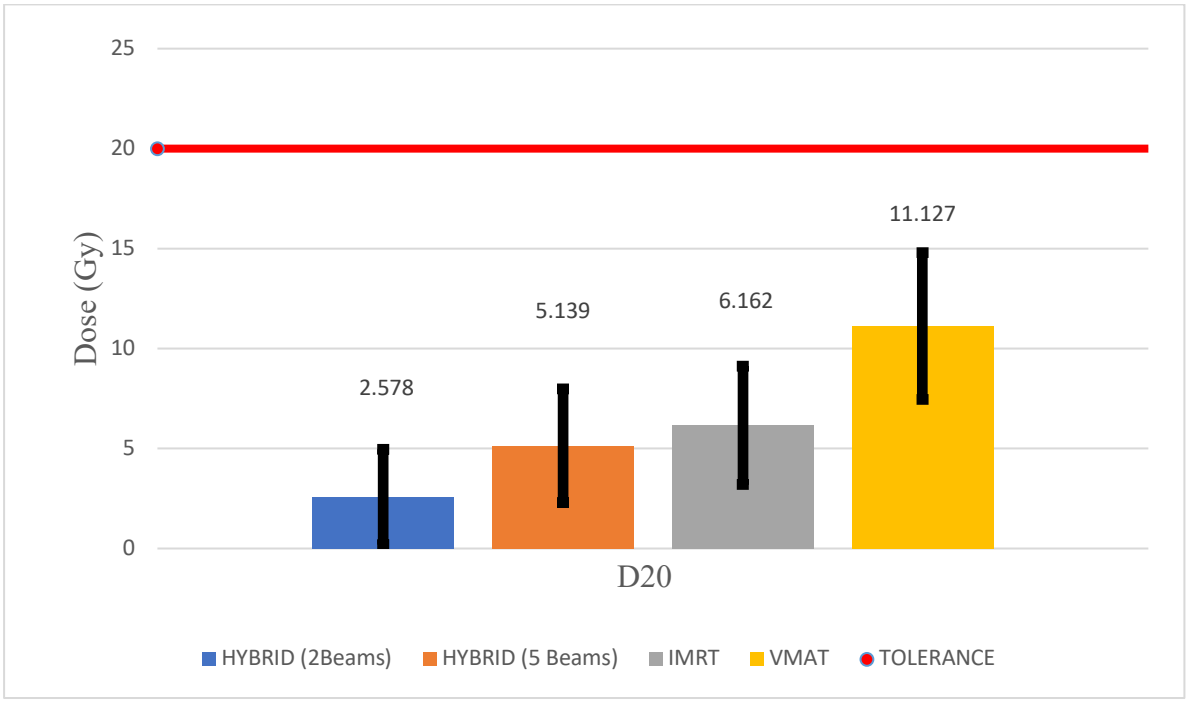

Figure 4.14 Mean doses to 20 % relative volume of the heart (chest-wall cases).

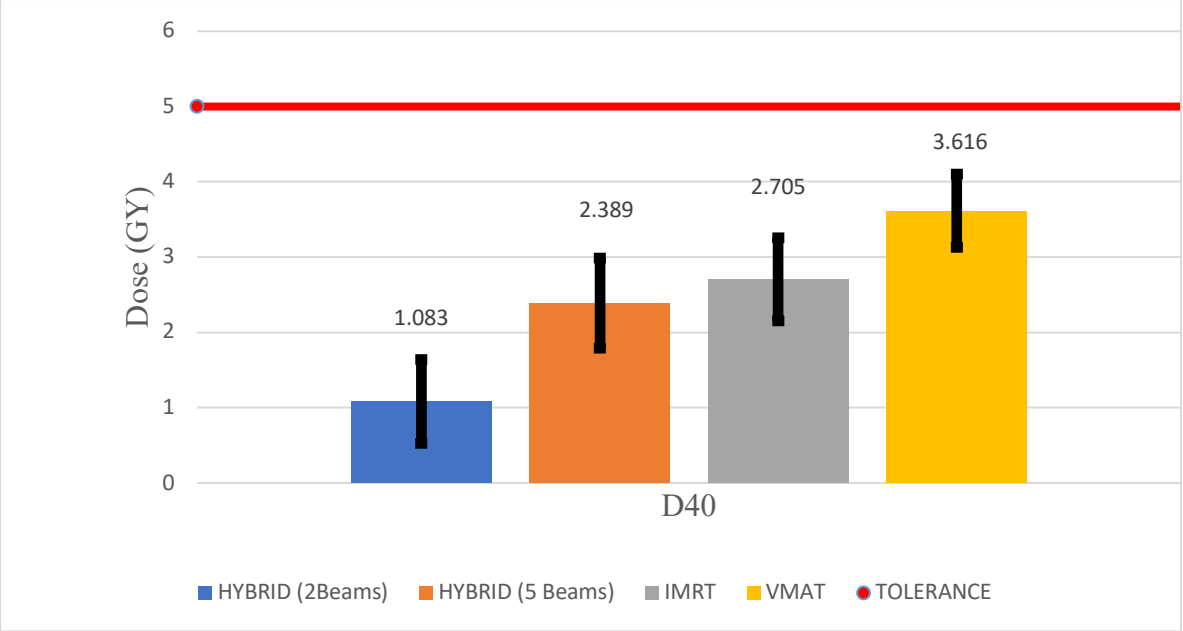

Figure 4.15 Mean doses to 40 % relative volume of the heart (chest-wall cases).

4.2.4 Dose Analysis of the Contralateral Breast

The analysis of the contralateral breast, evaluated using the D15% parameter, showed that the mean doses were 0.364 Gy ± 0.097 for Hybrid (2 Beams), 1.237 Gy ± 0.454 for Hybrid (5 Beams), 3.905 Gy ± 1.282 for IMRT, and 3.558 Gy ± 0.756 for VMAT. In Figure 4.18, the error bar representing the standard deviation is beyond the tolerance level for the IMRT plans. This indicates that some of the tolerances for the individual cases were not met as the dose received by the contralateral breast exceeded its tolerable limit. The lower doses associated with the hybrid techniques, particularly Hybrid (2 Beams), suggest a reduced risk of radiation-induced carcinogenesis in the contralateral breast, a known long-term complication of breast cancer radiotherapy.

Alsaihaty *et al*. (2024), found that hybrid techniques, such as Hybrid IMRT and Hybrid VMAT, offered better protection of the contralateral breast compared to full IMRT and VMAT plans. This observation aligns with the findings of this study, where the hybrid techniques consistently demonstrated lower doses to the contralateral breast. The choice of technique should, therefore,

consider the balance between effective target coverage and the minimisation of dose to OARs, particularly in cases where the contralateral breast is at risk. Figures 4.16 and 4.17 indicates the mean doses of the contralateral breast for all four techniques.

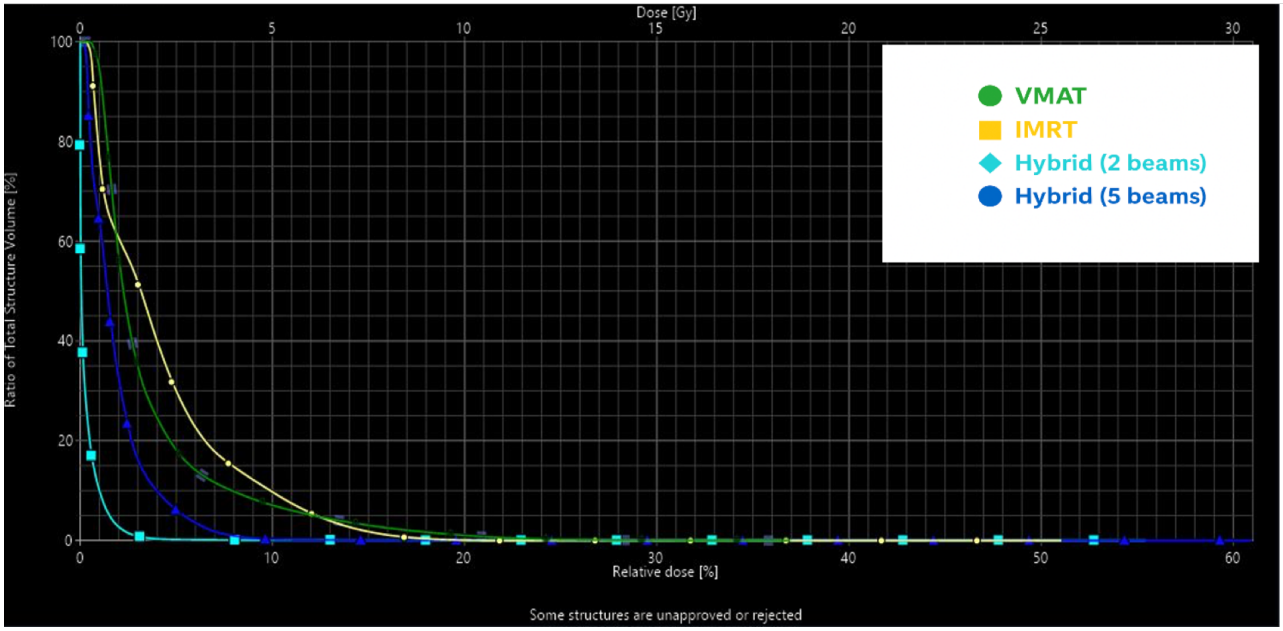

Figure 4.16 Dose volume histogram of the contralateral breast for all four techniques for a single patient (chest-wall).

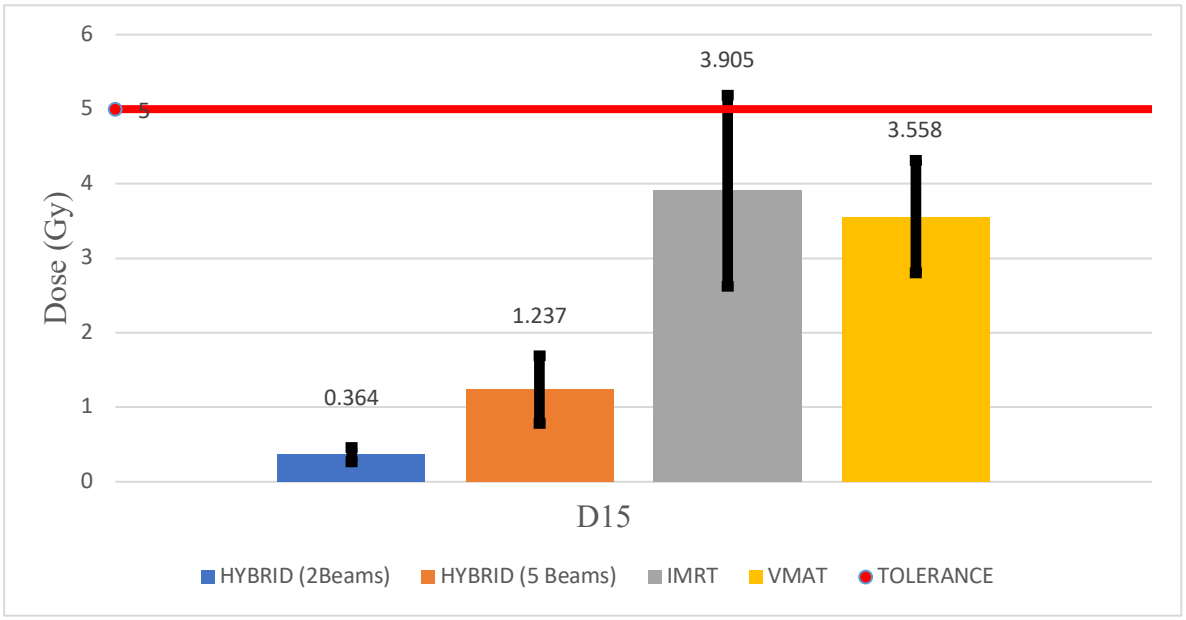

Figure 4.17 Mean doses to 15 % relative volume of the contralateral breast (chest-wall cases).

Table 4.2 Summary of mean OAR's dose volume histogram (DVH) parameters for four treatment plans (Chest Wall).

Structures	Hybrid (2 Beams)	Hybrid (5 Beams)	IMRT	VMAT	P-VALUE		
Heart					Hybrid (2 beams) vs HYBRID (5 beams)	Hybrid (2 beams) vs IMRT	Hybrid (2 beams) vs VMAT
D20 (Gy)	2.578 ± 2.385	5.139 ± 2.846	6.162 ± 2.960	11.127 ± 3.672	0.0006	6.2270×10^{-6}	1.3828×10^{-14}
D40 (Gy)	1.083 ± 0.557	2.389 ± 0.599	2.705 ± 0.552	3.616 ± 0.487	1.4178×10^{-11}	1.5900×10^{-15}	1.2400×10^{-24}
Ipsilateral lung							
D45 (Gy)	3.013 ± 0.875	8.281 ± 1.532	10.349 ± 1.851	12.528 ± 2.220	2.6735×10^{-22}	4.8397×10^{-26}	2.5094×10^{-28}
D35 (Gy)	4.891 ± 1.962	11.207 ± 1.994	13.260 ± 1.965	17.145 ± 2.329	4.9173×10^{-17}	1.7600×10^{-22}	4.5600×10^{-28}
Combined lung							
D25 (Gy)	2.464 ± 0.734	7.415 ± 1.729	9.911 ± 1.565	12.144 ± 2.076	7.2210×10^{-20}	5.2167×10^{-30}	4.3600×10^{-30}
D20 (Gy)	3.975 ± 1.991	9.725 ± 2.055	12.216 ± 1.575	14.719 ± 2.973	4.7097×10^{-15}	5.5500×10^{-24}	2.0900×10^{-22}
Contralateral Breast							
D15 (Gy)	0.364 ± 0.097	1.237 ± 0.454	3.905 ± 1.282	3.558 ± 0.756	0.0002	1.0900×10^{-6}	7.0300×10^{-10}

4.3 EVALUATION OF PTV FOR INTACT BREAST

4.3.1 HOMOGENEITY INDEX EVALUATION

The analysis of the homogeneity index (HI) for each intact breast cases across the four treatment techniques are presented in Figures 4.18 and 4.19. As revealed, there are notable variations in dose uniformity. As presented in Table 4.3, the Hybrid (5 Beams) technique demonstrated the most favourable dose homogeneity, with a mean HI value of 0.060 ± 0.011. This was closely followed by IMRT (0.065 ± 0.011), while Hybrid (2 Beams) exhibited a slightly higher HI value of 0.091 ± 0.020. VMAT had the highest HI value (0.104 ± 0.017), indicating a greater degree of dose variability within the target volume. These differences were statistically significant, particularly when comparing VMAT with the other techniques (p-value: 3.9854×10^{-12}).

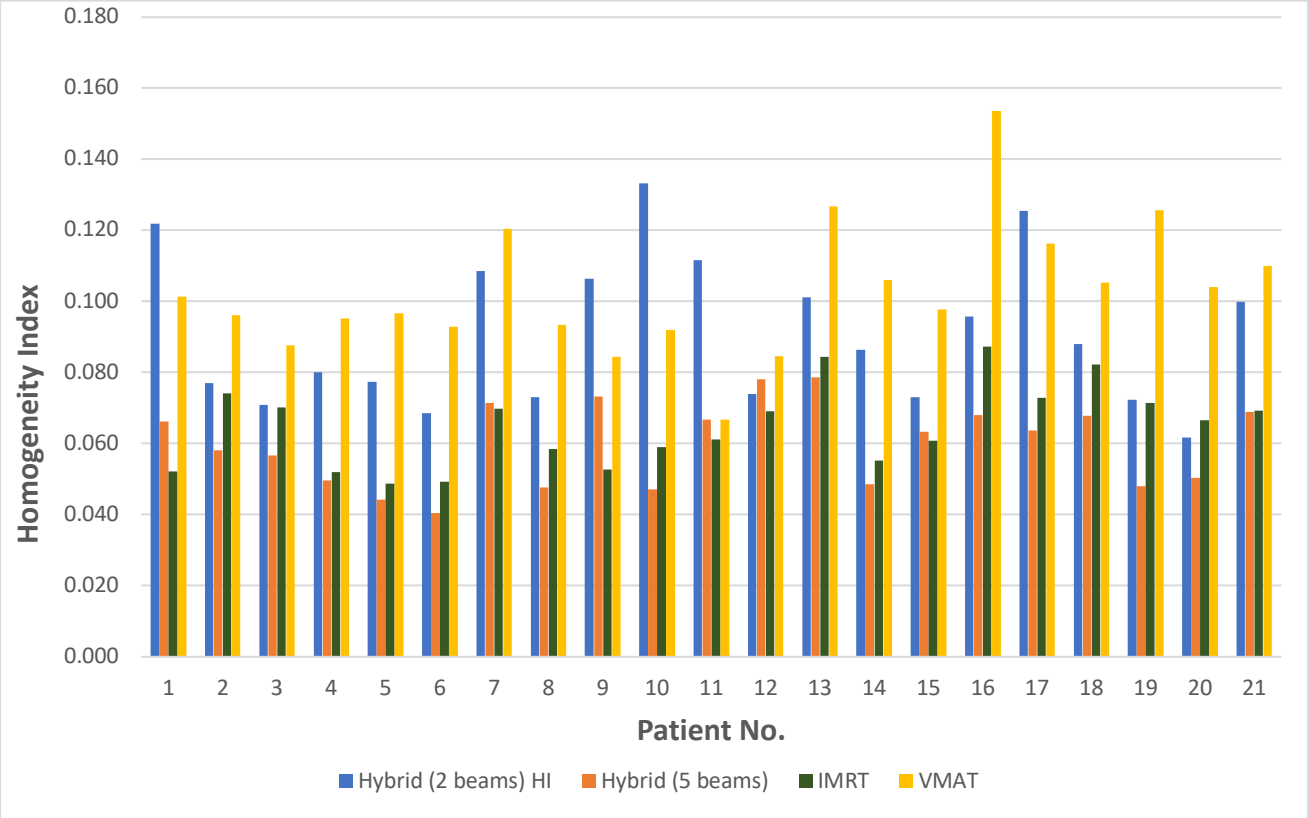

Figure 4.18 Histograms showing the homogeneity indices against the patient ID for all Intact breast cases.

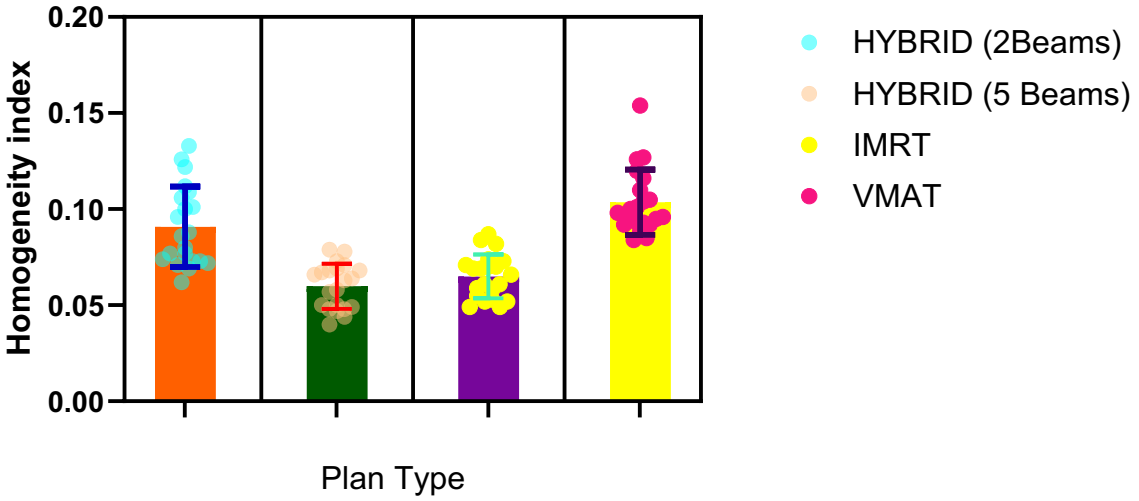

Figure 4.19 Homogeneity indices with their means and standard deviations of PTV for all intact-breast cases.

The trends observed in the intact breast cases are consistent with those found in chest wall cases. In both scenarios, the Hybrid (5 Beams) technique outperformed others regarding dose homogeneity, with an HI of 0.061 ± 0.008 for chest wall cases. However, the disparity between VMAT and the other techniques was more pronounced in the intact breast cases. This increased variability in HI for VMAT in intact breast cases may be attributed to the more complex tissue heterogeneities found in the intact breast compared to the chest wall, where tissue irregularities are less pronounced.

The superior homogeneity achieved with the Hybrid (5 Beams) technique can be attributed to its strategic combination of multiple fixed beams, which allows for better control of dose distribution, reducing hotspots and improving uniformity. This finding aligns with literature that highlights the effectiveness of hybrid techniques in balancing the advantages of conformal and intensity-modulated approaches. For instance, a study by Liu *et al*. (2020) reported that

hybrid techniques offer superior homogeneity by mitigating the effects of tissue heterogeneity, a benefit observed in both chest wall and intact breast treatments.

In comparison, Hybrid (2 Beams) showed slightly less favourable homogeneity in intact breast cases (HI = 0.091 ± 0.020) than in chest wall cases (HI = 0.071 ± 0.017). This difference could be due to the more complex anatomical structure of the intact breast, which may necessitate a more sophisticated beam arrangement to achieve the same level of homogeneity observed in chest wall treatments. (Awan *et al*. (2012), similarly noted that more complex anatomical sites require more complex planning to maintain dose uniformity, supporting the findings in this study.

VMAT consistently exhibited higher HI values in both intact breast and chest wall cases, underscoring the challenges it faces in achieving dose homogeneity. The dynamic delivery method of VMAT, which involves continuous modulation of beam intensity and gantry rotation, leads to greater dose variability. While VMAT excels in conformality, its ability to maintain uniformity is compromised, especially in anatomically complex regions such as the intact breast. This is consistent with findings from Zhao *et al*. (2016), who reported that VMAT, while highly conformal, often results in increased dose heterogeneity compared to other techniques. IMRT, while not as homogenous as Hybrid (5 Beams), performed reasonably well in maintaining dose uniformity across both intact breast and chest wall cases. The HI value for IMRT in intact breast cases (0.065 ± 0.011) is slightly higher than that for Hybrid (5 Beams), but significantly better than that for VMAT. This suggests that while IMRT remains a viable option, it may not outperform Hybrid (5 Beams) in cases where anatomical complexity is a factor. Mishra *et al*. (2023) observed similar trends, noting that while IMRT provides good homogeneity, it is often surpassed by hybrid techniques in more complex anatomical regions.

The clinical implications of these findings are significant, particularly concerning long-term patient outcomes. The superior homogeneity observed with Hybrid (5 Beams) is crucial for minimising complications such as radiation-induced fibrosis and ensuring the prescribed dose is uniformly delivered across the target volume. This finding is supported by a study by Karaca, (2022), which demonstrated that hybrid techniques are effective in reducing dose variability and improving homogeneity in breast cancer radiotherapy.

4.3.2 CONFORMITY INDEX EVALUATION

The conformity indices (CI) for the intact breast cases were evaluated across the four treatment techniques; Hybrid (2 Beams), Hybrid (5 Beams), IMRT, and VMAT as shown in Table 4.3. VMAT again demonstrated the best conformity with a mean CI of 1.018 ± 0.036, followed by IMRT (1.118 ± 0.041), Hybrid (5 Beams) (1.186 ± 0.054), and Hybrid (2 Beams) (1.217 ± 0.097). The data as indicated in Figures 4.22 and 4.23, shows that VMAT consistently provided the most conformal dose distributions, a trend observed in both intact breast and chest wall cases, although the conformity was slightly better in the intact breast cases as indicated by the lower CI values across all techniques.

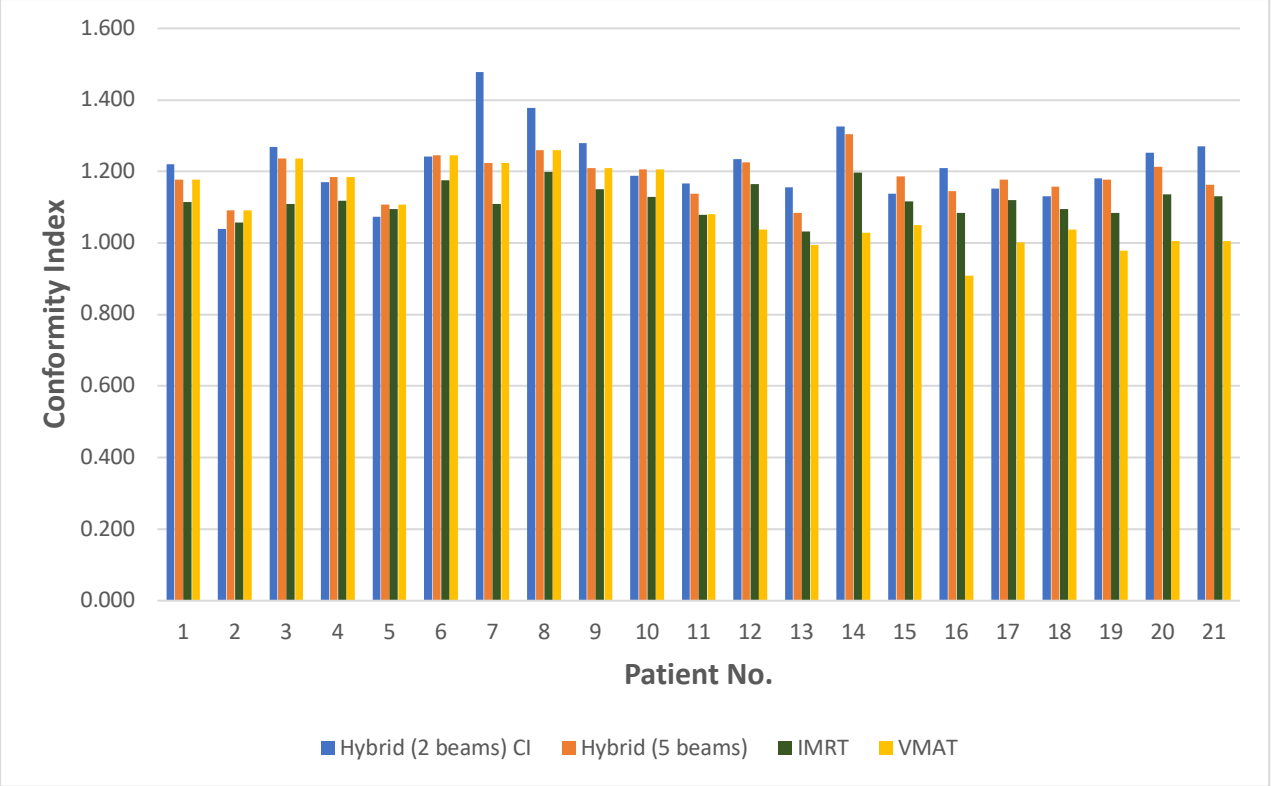

Figure 4.20 Histograms showing the conformity indices against the patient id for all intact breast cases.

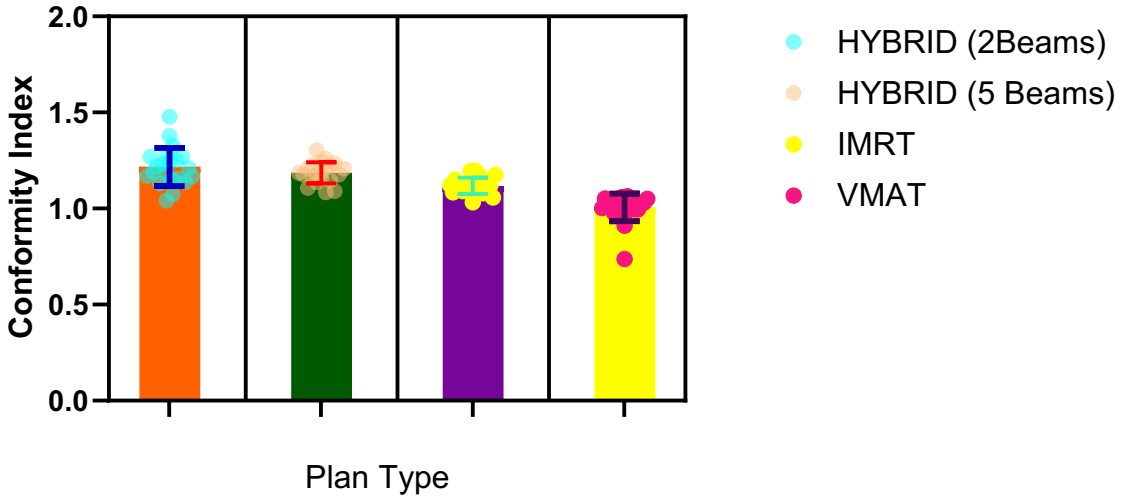

Figure 4.21 Conformity indices with their means and standard deviations of PTV for all intact breast cases.

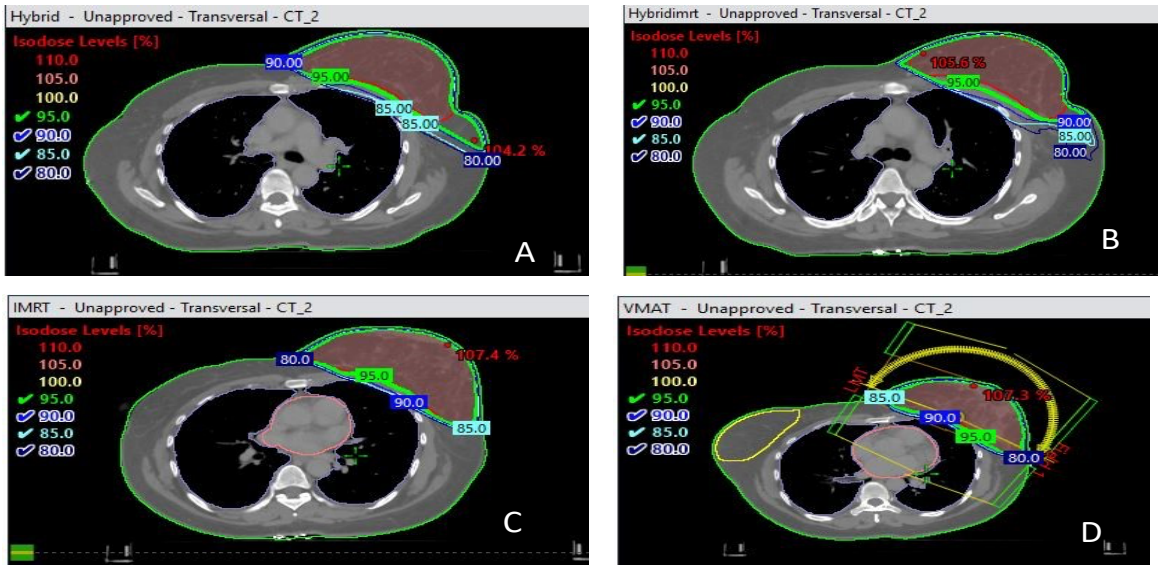

Figure 4.22 Axial CT images with contoured structures and dose distribution for the four techniques; A. Hybrid (2 beams), B. Hybrid (5 Beams), C. IMRT, D. VMAT.

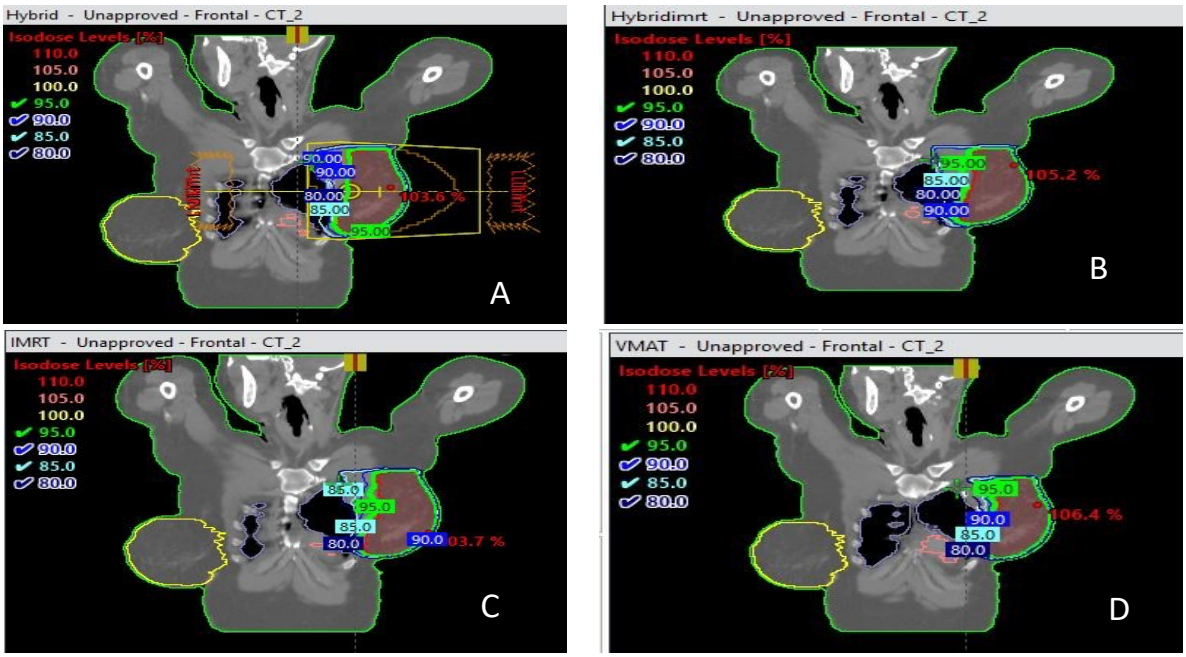

Figure 4.23 Coronal CT images with contoured structures and dose distribution for the four techniques; A. Hybrid (2 beams), B. Hybrid (5 Beams), C. IMRT, and D. VMAT.

The improvement in conformity for intact breast cases with VMAT is consistent with findings in the literature, where VMAT is frequently cited for its ability to deliver highly conformal

doses due to its dynamic arc-based delivery. Studies like those by De Rose *et al*., (2016) and Zhao *et al*., (2015) have noted VMAT's superior performance in conformality due to its continuous modulation of beam intensity and dose rate as the gantry rotates around the patient, enabling precise targeting of the tumour while sparing adjacent healthy tissues.

For the IMRT technique, the CI value of 1.118 ± 0.041 for intact breast cases suggests a good level of conformity, though not as strong as VMAT. When compared to the chest wall cases, IMRT for intact breasts shows a slightly better CI, indicative of the more consistent tissue geometry and potentially fewer challenges in beam modulation. This slight improvement is aligned with Nakamura *et al*. (2014), who noted that while IMRT generally provides good conformity, its performance can be impacted by the complexity of the target volume and the presence of surrounding organs at risk (OARs), which may be less of an issue in intact breast cases compared to chest wall cases.

Hybrid techniques, particularly the 5-beam approach, showed a mean CI of 1.186 ± 0.054 in intact breast cases, which, while less conformal than IMRT and VMAT, still falls within acceptable ranges according to the Radiation Therapy Oncology Group (RTOG) guidelines. The slight improvement in CI compared to the chest wall cases (where Hybrid 5-Beams had a CI of 1.325 ± 0.099) suggests that the additional beams in the hybrid plan may better handle the less complex geometry of the intact breast, reducing the irradiation of surrounding tissues more effectively than in chest wall cases. The Hybrid (2 Beams) approach, with a CI of 1.217 ± 0.097, shows the least conformity, mirroring the results observed in chest wall cases. This technique, while still within the acceptable CI range of $1 < CI \leq 1.5$, suggests that the simpler beam arrangement may not be as effective in sparing adjacent healthy tissues, leading to broader dose distributions. Cozzi *et al*. (2017) found similar results, where simpler techniques often resulted in higher CI values due to their less refined dose modulation, which can be more

pronounced in complex target areas like the chest wall but remains relevant in intact breast cases as well.

In the analysis of VMAT plans, five individual CI values fell below 1, that is 0.989, 0.982, 0.996, 0.910, and 0.978. A CI value below 1 suggests potential under-coverage of the target volume, meaning that parts of the breast tissue may not have received the full prescribed radiation dose. Clinically, this raises concerns about the possibility of tumour cells within these under-covered regions not receiving an adequate dose, which could compromise the treatment's effectiveness and increase the risk of local recurrence. Moreover, a CI value below 1 could indicate a geometric miss where the high-dose region does not fully encompass the intended target. This might result from factors like patient movement, inaccuracies in treatment planning, or limitations in the delivery system. While VMAT generally provides excellent conformity, these instances highlight the importance of rigorous plan evaluation and, if necessary, the use of adaptive planning techniques to ensure complete and consistent dose coverage.

Overall, the results indicate that while all techniques provided conformal dose distributions within clinically acceptable ranges, VMAT stands out as the most conformal technique for intact breast cases, as it did for chest wall cases, though with slightly better overall performance in the intact breast. IMRT also shows robust performance, particularly in more uniform target volumes like the intact breast, while Hybrid techniques, particularly those with more beams, offer a reasonable balance but with less precision than the more advanced techniques like VMAT and IMRT. These findings underscore the importance of technique selection based on target complexity and the need to balance conformity with other factors like treatment time and potential risks to OARs.

Table 4.3 Summary of PTV dose volume histogram (DVH) parameters for four treatment plans (Intact Breast).

Structures	Hybrid (2 Beams)	Hybrid (5 Beams)	IMRT	VMAT	*P-Value*		
PTV					Hybrid (5beams) vs hybrid (2beams)	Hybrid (5beams) vs IMRT	Hybrid (5beams) vs VMAT
D2 (Gy)	52.04 ± 0.764	51.66 ± 0.433	51.69 ± 0.321	52.38 ± .0418	0.0559	0.8049	3.2470×10^{-6}
D50 (Gy)	50.15 ± 0.158	49.97 ± 0.108	49.95 ± 0.059	50.06 ± 0.150	0.0002	0.4659	0.0416
D98 (Gy)	47.49 ± 0.536	48.67 ± 0.217	48.44 ± 0.327	47.20 ± 0.537	2.8262×10^{-11}	0.0125	4.6530×10^{-14}
HI	0.091 ± 0.020	0.060 ± 0.011	0.065 ± 0.011	0.104 ± 0.017	5.8077×10^{-7}	0.152	3.9854×10^{-12}
					VMAT vs Hybrid (2 beams)	VMAT vs Hybrid (5 beams)	VMAT Vs IMRT
CI	1.217 ± 0.097	1.186 ± 0.054	1.118 ± 0.041	1.018 ± 0.036	1.3587×10^{-10}	2.6472×10^{-14}	5.4177×10^{-10}
					VMAT vs Hybrid (2 beams)	VMAT vs Hybrid (5 beams)	VMAT Vs IMRT
MU	413.1 ± 55.5	828.1 ± 78.6	1036.2 ± 129.8	410.1 ± 53.6	0.8629	3.7506×10^{-22}	2.1741×10^{-22}

4.4 DOSE ANALYSIS OF OARS (INTACT BREAST)

4.4.1 Dose Analysis of the ipsilateral lung

As summarised in Table 4.4, the dose parameters used in evaluating the ipsilateral lung for intact breast cases were D35% and D45%. The mean dose to the D45% volume of the ipsilateral lung was found to be 2.351 Gy ± 0.090 for the Hybrid (2 Beams) technique, 6.623 Gy ± 2.270 for Hybrid (5 Beams), 10.689 Gy ± 1.945 for IMRT, and 12.305 Gy ± 1.814 for VMAT as shown in Figure 4.24. Similarly, the D35% volume recorded mean doses of 3.497 Gy ± 1.691, 8.415 Gy ± 3.346, 12.844 Gy ± 2.551, and 15.651 Gy ± 2.091 for Hybrid (2 Beams), Hybrid (5 Beams), IMRT, and VMAT, respectively. This is shown in Figure 4.25.

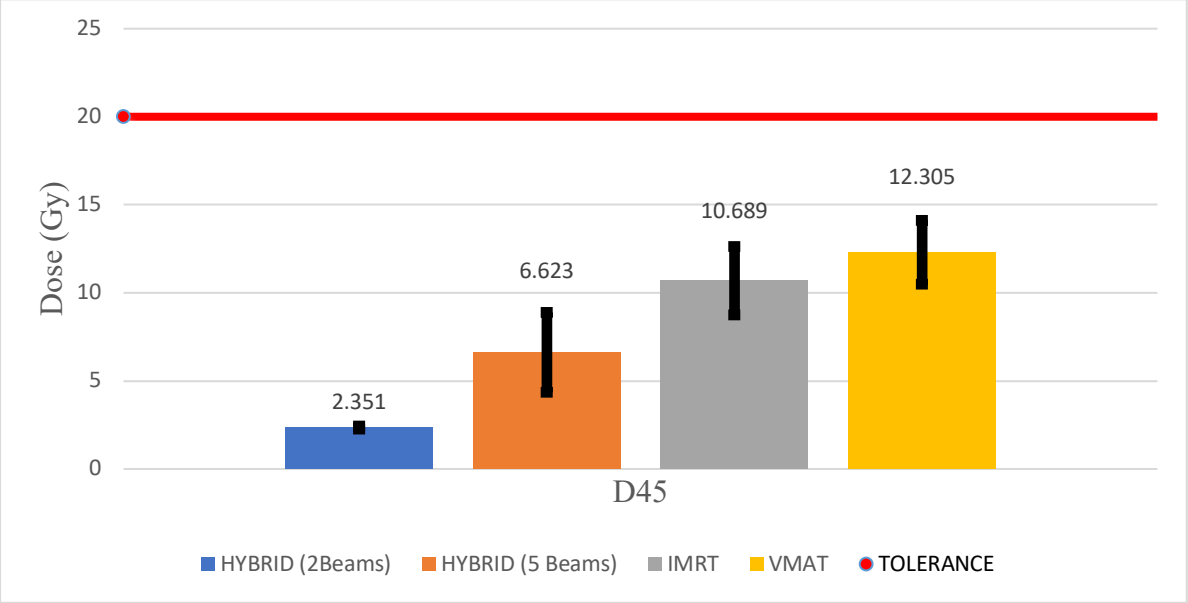

Figure 4.24 Mean doses to 35 % relative volume of the ipsilateral lung (intact breast cases).

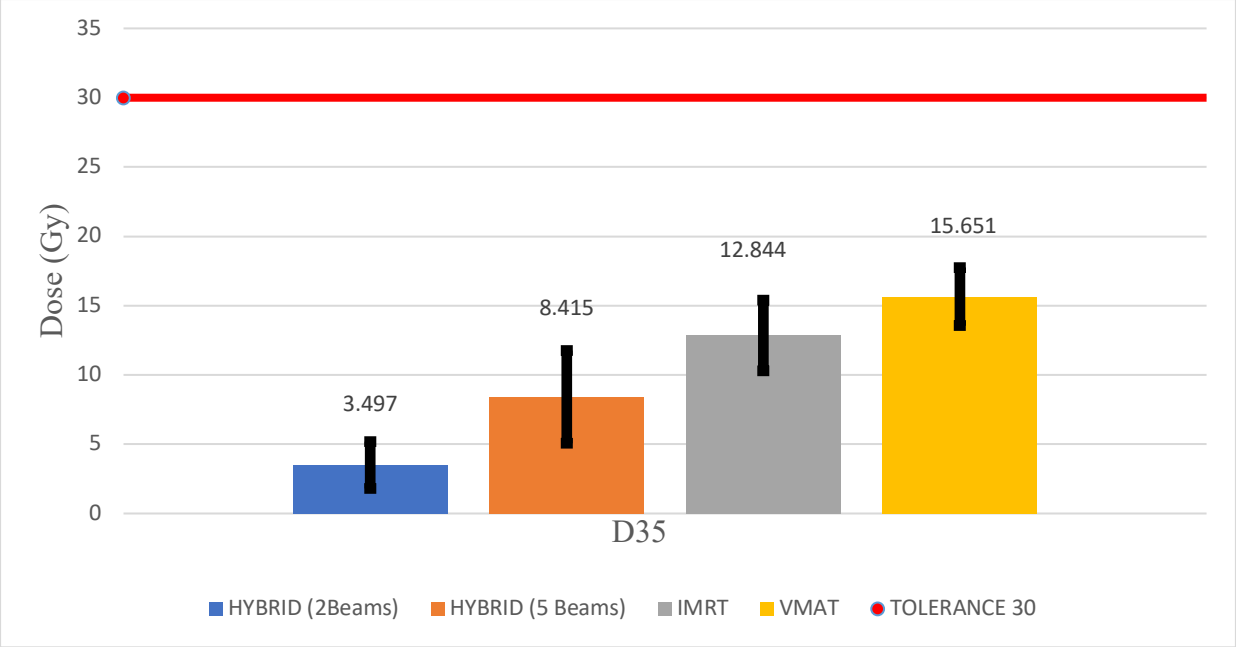

Figure 4.25 Mean doses to 45 % relative volume of the ipsilateral lung (intact breast cases).

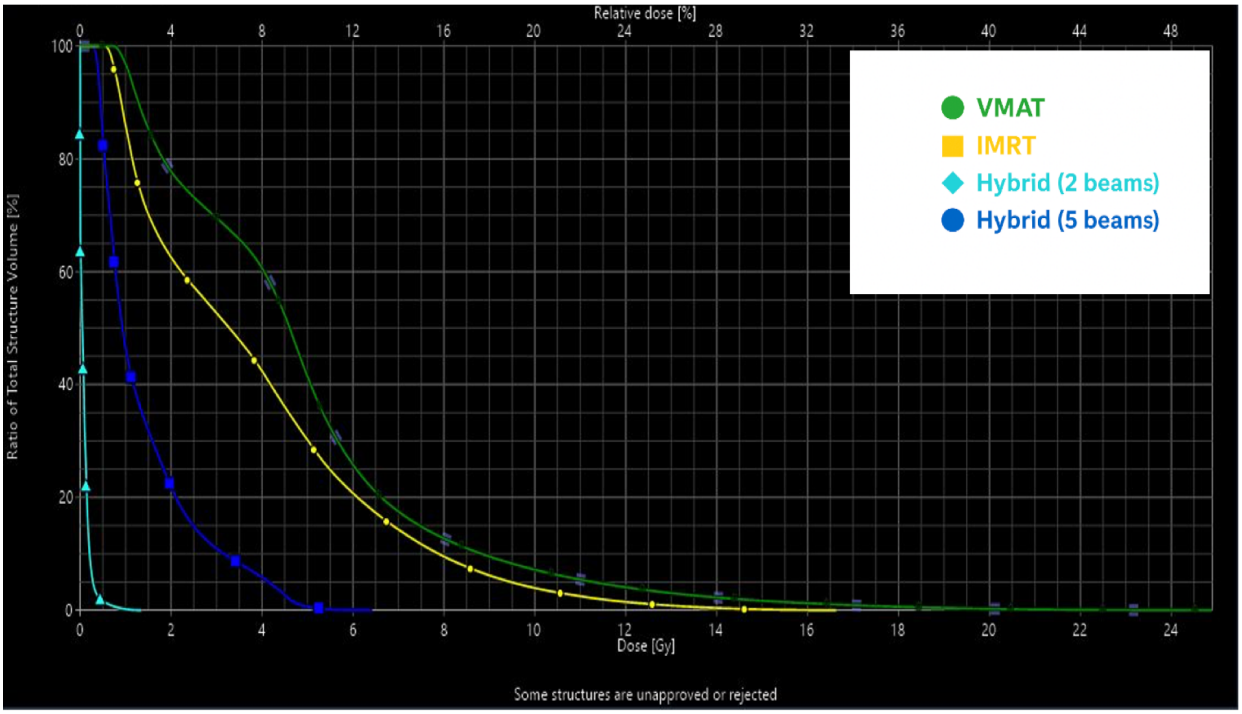

Figure 4.26 Dose volume histogram of the ipsilateral lung for all four techniques for a single patient (intact breast case).

The findings indicate that VMAT resulted in the highest dose to the ipsilateral lung, followed by IMRT, Hybrid (5 Beams), and Hybrid (2 Beams). These results align with previous studies,

such as those by Haciislamoglu *et al*. (2019), which highlighted the increased dose to the ipsilateral lung with advanced techniques like VMAT. While offering superior target coverage and conformity, these techniques tend to involve more complex beam arrangements that can inadvertently increase the dose to nearby healthy tissues, including the ipsilateral lung. The literature suggests that higher doses to the ipsilateral lung increase the risk of radiation pneumonitis (RP), a condition characterised by inflammation and fibrosis of lung tissue within the irradiated volume (Smith *et al*., 2018).

Given that VMAT and IMRT delivered substantially higher doses to the ipsilateral lung than the hybrid techniques, these advanced techniques may pose a greater risk for lung toxicity. However, it is noteworthy that despite these higher doses, all four techniques met the desired dose constraints, aligning with the recommendations by Taylor *et al*. (2017) regarding lung dose limitations in breast cancer radiotherapy.

4.4.2 Dose Analysis of the Combined Lungs

The combined lungs were analysed using dose parameters of D20% and D25%. The data revealed that the mean dose to the D25% volume of the combined lungs was 2.108 Gy ± 0.883 for Hybrid (2 Beams), 6.249 Gy ± 2.154 for Hybrid (5 Beams), 10.783 Gy ± 1.906 for IMRT, and 11.844 Gy ± 2.295 for VMAT. For the D20% volume, the mean doses were 2.921 Gy ± 1.385, 7.581 Gy ± 2.753, 12.359 Gy ± 2.136, and 14.011 Gy ± 2.449 for Hybrid (2 Beams), Hybrid (5 Beams), IMRT, and VMAT, respectively.

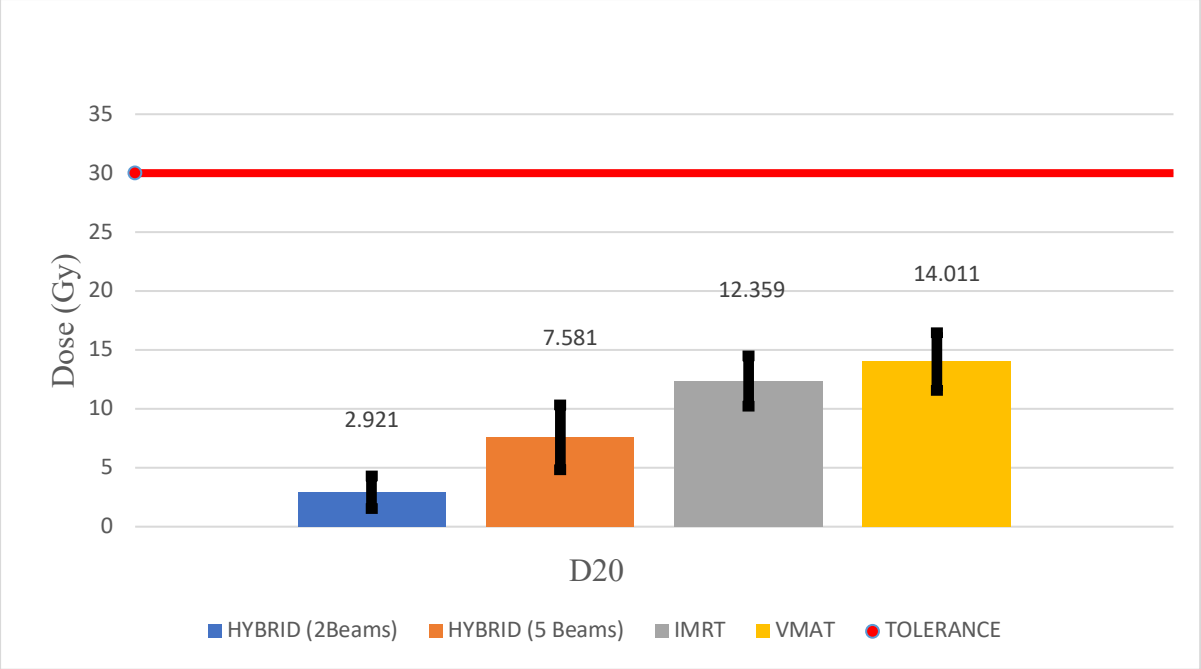

Figure 4.27 Mean doses to 20% relative volume of the combined lungs (intact breast cases).

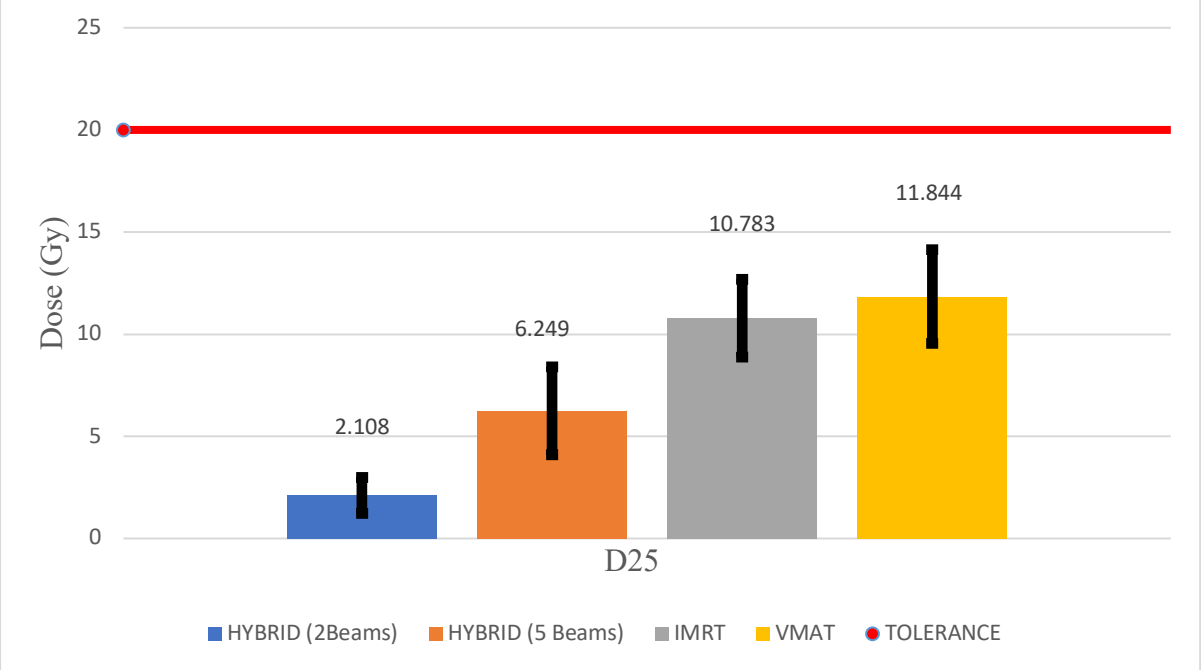

Figure 4.28 Mean doses to 25% relative volume of the combined lungs (intact breast cases).

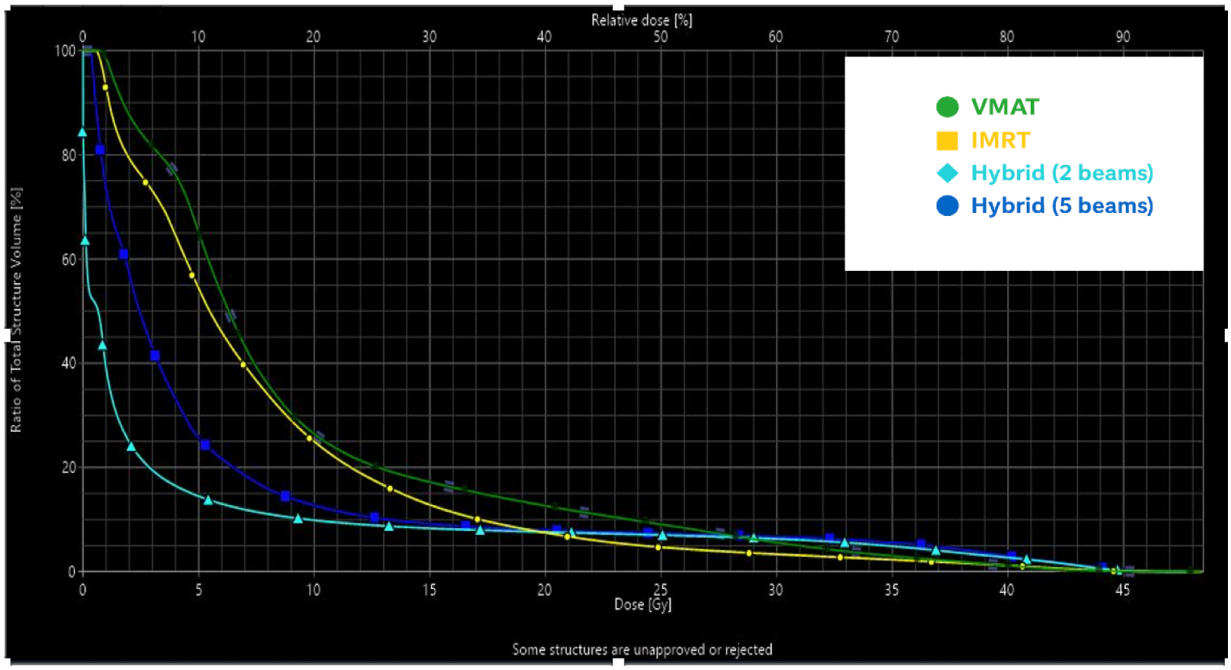

Figure 4.29 Dose volume histogram of the combined lungs for all four techniques for a single patient (intact breast case).

As with the ipsilateral lung, the VMAT technique resulted in the highest dose to the combined lungs, followed by IMRT, Hybrid (5 Beams), and Hybrid (2 Beams) as indicated in Figures 4.27, 4.28, and 4.29. This outcome is particularly noteworthy in intact breast irradiation, where the contralateral lung is at risk of incidental radiation exposure. Increased dose to the combined lungs observed with VMAT and IMRT can be attributed to the wider arc and multiple beam angles used in these techniques, which, while enhancing dose conformity to the target, can unintentionally increase dose spillage into adjacent normal tissues.

The clinical significance of these findings is critical, especially in patients with pre-existing pulmonary conditions. Excessive doses to the combined lungs could lead to long-term complications such as radiation-induced lung injury, as suggested by Gueiderikh *et al*. (2023). The choice of technique, therefore, must balance the need for effective target coverage with the minimisation of dose to the lungs, particularly in cases where both lungs are at risk.

4.4.3 Dose Analysis of the Heart

The heart is a critical organ at risk (OAR) in intact breast irradiation. The mean dose to the D40% volume of the heart was 0.982 Gy ± 0.561 for Hybrid (2 Beams), 2.498 Gy ± 0.577 for Hybrid (5 Beams), 2.786 Gy ± 0.626 for IMRT, and 3.678 Gy ± 0.720 for VMAT. For the D20% volume, the mean doses were 2.431 Gy ± 2.195, 4.803 Gy ± 2.040, 6.599 Gy ± 2.326, and 10.043 Gy ± 4.467 for Hybrid (2 Beams), Hybrid (5 Beams), IMRT, and VMAT, respectively.

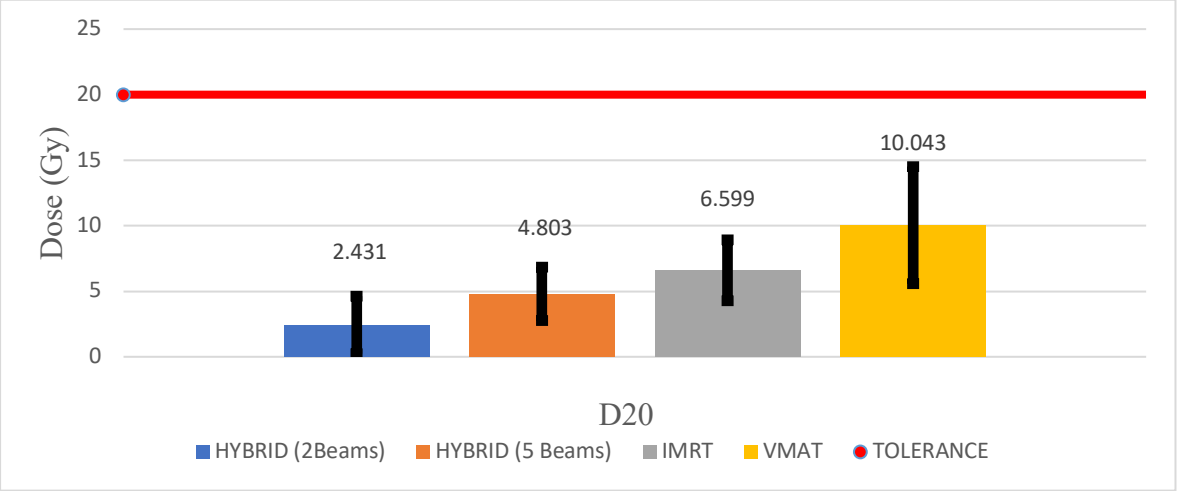

Figure 4.30 Mean doses to 20% relative volume of the heart (intact breast cases).

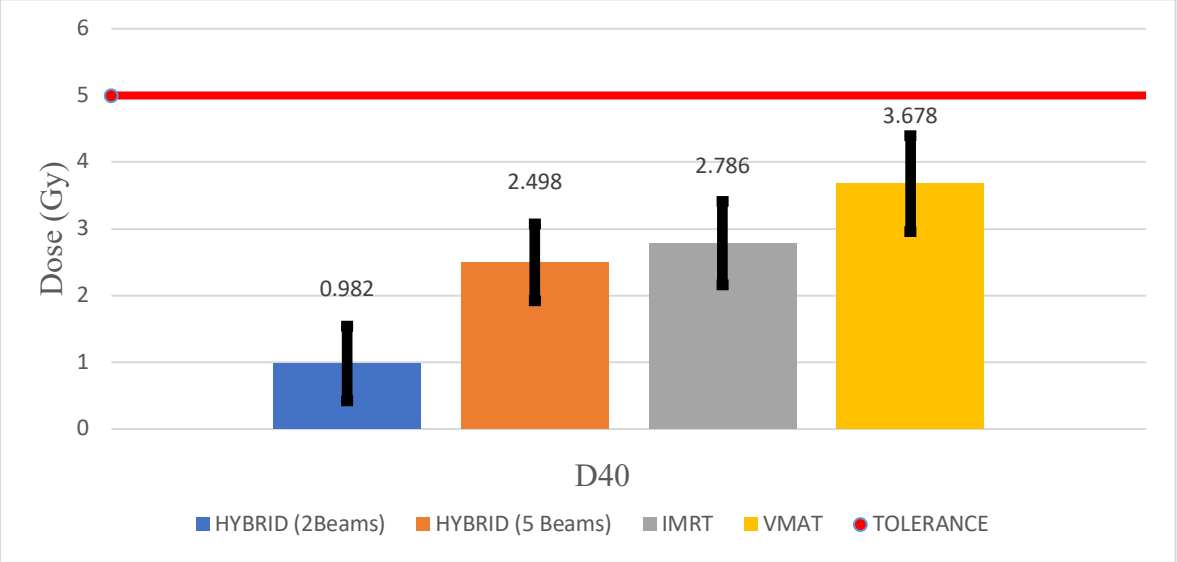

Figure 4.31 Mean doses to 25% relative volume of the heart (intact breast cases).

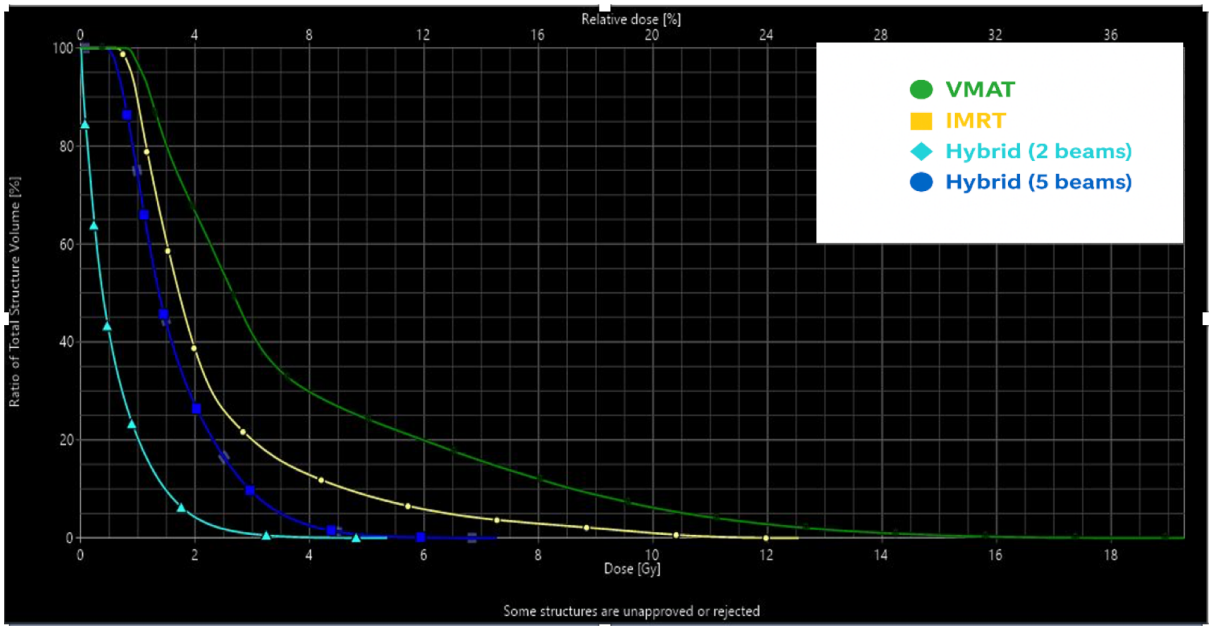

Figure 4.32 Dose volume histogram of the heart for all four techniques for a single patient (intact breast case).

The results indicate that the Hybrid (2 Beams) technique provided the most significant sparing of the heart, followed by Hybrid (5 Beams), IMRT, and VMAT. This is observed in Figures 4.30, 4.31, and 4.32. The higher doses associated with VMAT and IMRT, compared to hybrid techniques, raise concerns about the long-term risk of cardiac complications. The findings by Taylor *et al*. (2017) underline the increased risk of cardiovascular disease with higher heart doses, particularly in patients with pre-existing heart conditions. The literature suggests that doses to the heart should be minimised to reduce the risk of radiation-induced heart disease, which can manifest years after treatment Darby *et al*. (2013). These findings emphasise the importance of careful technique selection, particularly for patients with significant cardiac comorbidities.

4.4.4 Dose Analysis of the Contralateral Breast

The analysis of the contralateral breast, evaluated using the D15% parameter, showed that the mean doses were 0.405 Gy ± 0.295 for Hybrid (2 Beams), 1.184 Gy ± 0.396 for Hybrid (5 Beams), 3.188 Gy ± 1.141 for IMRT, and 4.183 Gy ± 1.131 for VMAT. The lower doses associated with the hybrid techniques, particularly Hybrid (2 Beams), suggest a reduced risk of radiation-induced carcinogenesis in the contralateral breast, a known long-term complication of breast cancer radiotherapy.

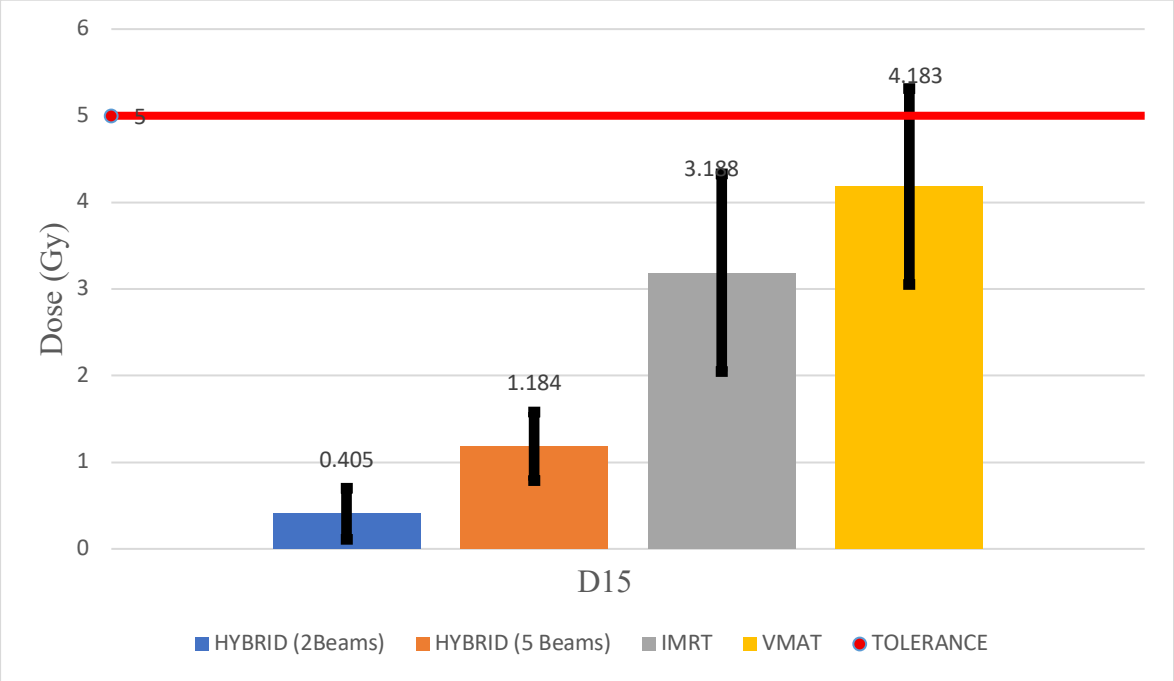

Figure 4.33 Mean doses to 15% relative volume of the contralateral breast (intact breast cases).

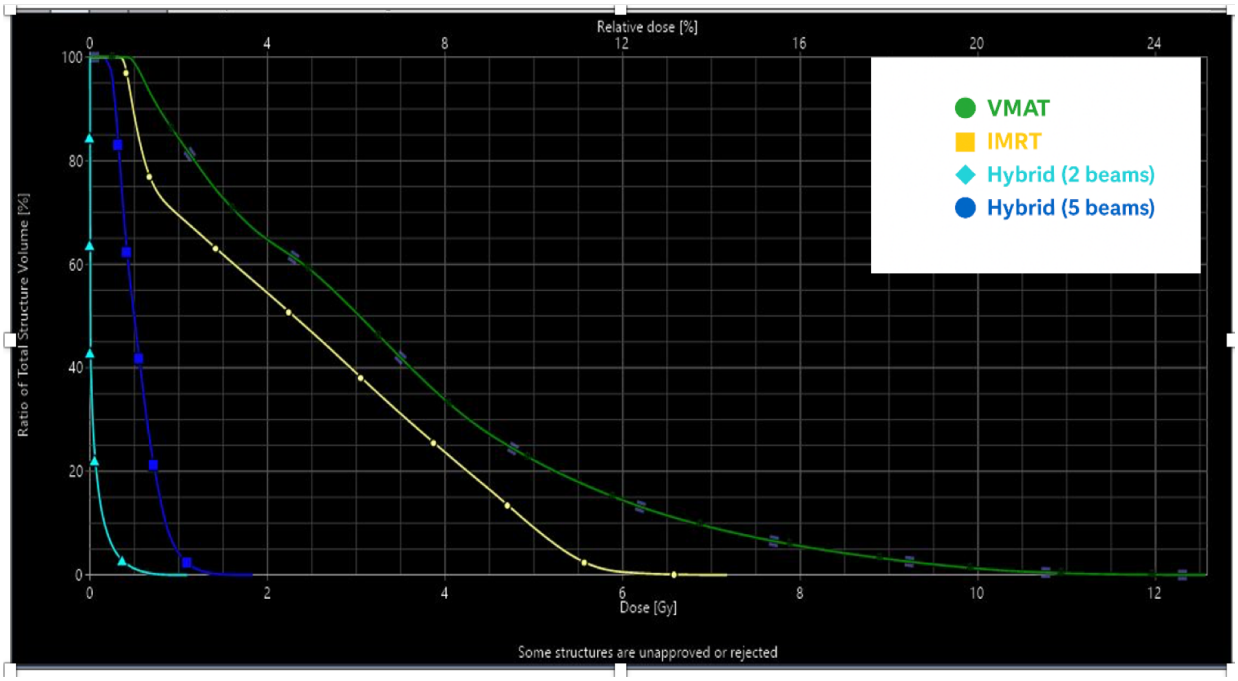

Figure 4.34 Dose volume histogram of the contralateral breast for all four techniques for a single patient (intact breast case).

These results align with the findings of Haciislamoglu *et al*. (2019), who found that hybrid techniques offered better protection of the contralateral breast compared to full IMRT and VMAT plans. The choice of technique should therefore consider the balance between effective target coverage and the minimisation of dose to OARs, particularly in cases where the contralateral breast is at risk.

Table 4.4 Summary of OAR's dose volume histogram (DVH) parameters for four treatment plans (Intact Breast).

Structures	Hybrid (2 Beams)	Hybrid (5 Beams)	IMRT	VMAT	P-VALUE		
Heart					Hybrid (2 beams) vs HYBRID (5 beams)	Hybrid (2 beams) vs IMRT	Hybrid (2 beams) vs VMAT
D20 (Gy)	2.431 ± 2.195	4.803 ± 2.040	6.599 ± 2.326	10.043 ± 4.467	0.0010	8.2350×10^{-7}	3.1340×10^{-8}
D40 (Gy)	0.982 ± 0.561	2.498 ± 0.577	2.786 ± 0.626	3.678 ± 0.720	2.0842×10^{-10}	6.1500×10^{-12}	3.5900×10^{-16}
Ipsilateral lung							
D45 (Gy)	2.351 ± 0.090	6.623 ± 2.270	10.689 ± 1.945	12.305 ± 1.814	1.4234×10^{-9}	3.0899×10^{-20}	6.4669×10^{-24}
D35 (Gy)	3.497 ± 1.691	8.415 ± 3.346	12.844 ± 2.551	15.651 ± 2.091	7.2796×10^{-7}	1.2000×10^{-16}	1.3300×10^{-21}
Combined lung							
D25 (Gy)	2.108 ± 0.883	6.249 ± 2.154	10.783 ± 1.906	11.844 ± 2.295	9.1469×10^{-10}	3.4875×10^{-21}	7.8700×10^{-20}
D20 (Gy)	2.921 ± 1.385	7.581 ± 2.753	12.359 ± 2.136	14.011 ± 2.449	4.0166×10^{-8}	1.5900×10^{-19}	1.8300×10^{-20}
Contralateral Breast							
D15 (Gy)	0.405 ± 0.295	1.184 ± 0.396	3.188 ± 1.141	4.183 ± 1.131	0.25540	0.0107	0.0022

4.5 MONITOR UNIT EVALUATION (CHEST-WALL AND INTACT BREAST)

In radiotherapy, monitor units (MU) are a critical factor in determining the efficiency and complexity of treatment delivery and time. The results of the study present a clear distinction in the MU that was recorded for various breast irradiation techniques for both chest wall and intact breast cases, reflecting the inherent complexity and sophistication of each method.

For chest wall cases, the Hybrid (2 Beams) technique required the fewest MUs, averaging 388.3 ± 20.2, while for intact breast cases, it was slightly higher at 413.1 ± 55.5. This indicates that the Hybrid (2 Beams) technique remains the most efficient in terms of radiation delivery, with minimal machine demands and reduced treatment times for both scenarios. However, its simplicity, as mentioned earlier, may lead to less precise dose distribution, potentially compromising the conformality of the treatment plan, as seen in studies like Li *et al*. (2021). The slightly higher MUs in intact breast cases may suggest additional challenges in dose delivery, possibly due to the more complex anatomical structures involved.

The Hybrid (5 Beams) technique showed a significant increase in MUs for both chest wall and intact breast cases, with averages of 729.0 ± 80.7 and 828.1 ± 78.6, respectively. This is shown in tables 3.37 and 4.38. The increased MU requirement reflects the technique's enhanced dose modulation capabilities, which improve dose conformity and coverage but also lead to greater complexity and longer treatment times. The higher MU in intact breast cases could be attributed to the need for more precise dose delivery due to the proximity of critical structures, aligning with findings from Zhang *et al*. (2024) on the benefits and challenges of multi-beam approaches.

IMRT, known for its advanced modulation, required the highest MUs among the static techniques, with chest wall cases averaging 949.1 ± 81.2 and intact breast cases even higher at 1036.2 ± 129.8. This increase in MUs corresponds to the need for complex modulation to

achieve the desired dose distribution, particularly in intact breast cases where the anatomical structures may necessitate more intricate planning. Suyan *et al*. (2022) highlighted the implications of such high MUs, including the potential for machine-related errors and increased patient discomfort due to longer treatment sessions. The higher MU in intact breast cases underscores the added complexity and challenges posed by the more varied anatomical landscape.

VMAT, despite its dynamic delivery method, required fewer MUs than IMRT in both scenarios, with chest wall cases averaging 434.6 ± 43.9 and intact breast cases at 410.1 ± 53.6. This efficiency is due to VMAT's ability to deliver radiation in a continuous arc, optimising dose delivery and reducing the number of required beam-on times. Interestingly, the MU for intact breast cases is slightly lower than for chest wall cases, potentially reflecting the technique's adaptability to the varying anatomical complexities of the breast. Studies such as Zhao *et al*., (2015), have demonstrated VMAT's superiority in achieving dose conformality with fewer MUs, making it a highly efficient technique for both chest wall and intact breast irradiation.

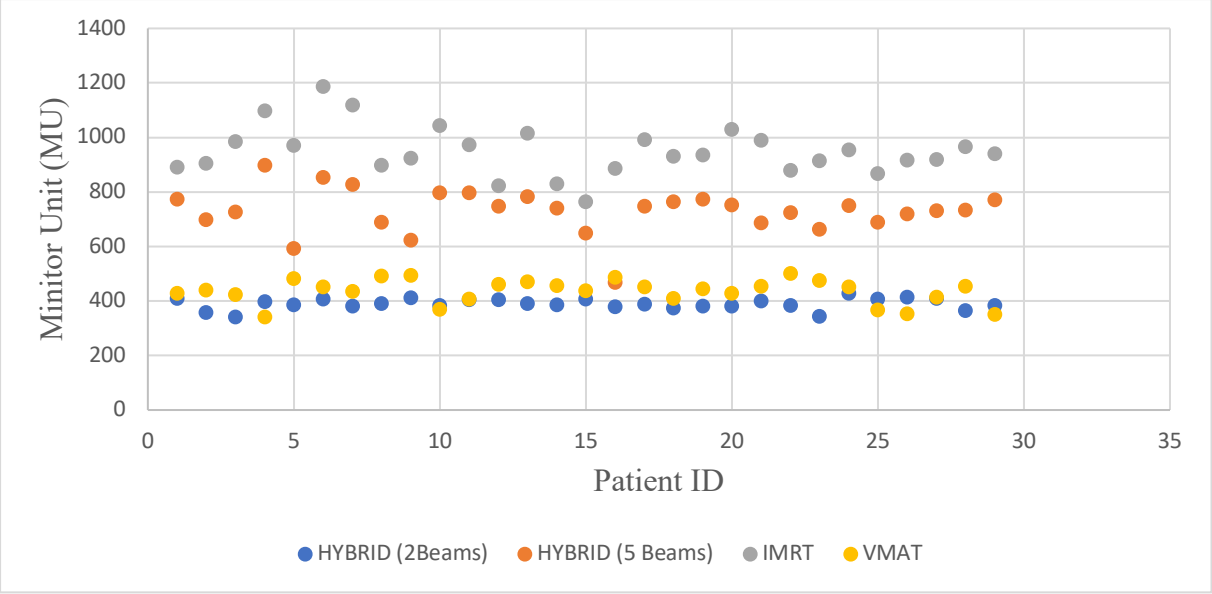

Figure 4.35 Dot plot of monitor units (MU) per 2 Gy of a technique for all Chest-wall cases.

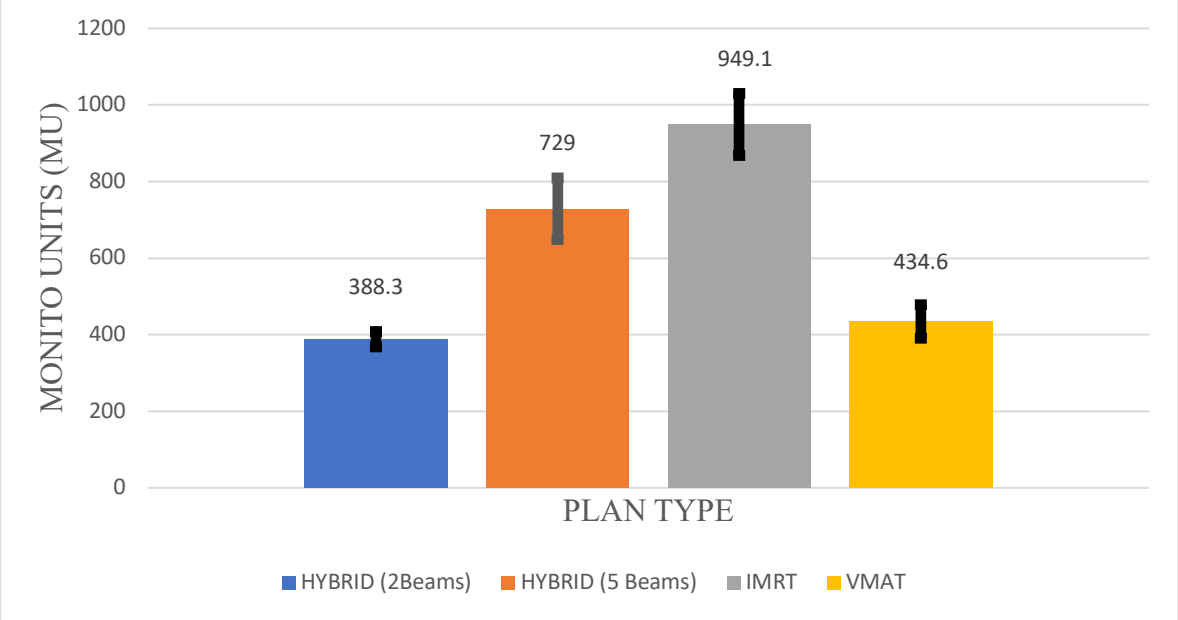

Figure 4.36 Average monitor units (MU) per 2 Gy of a technique for chest-wall cases.

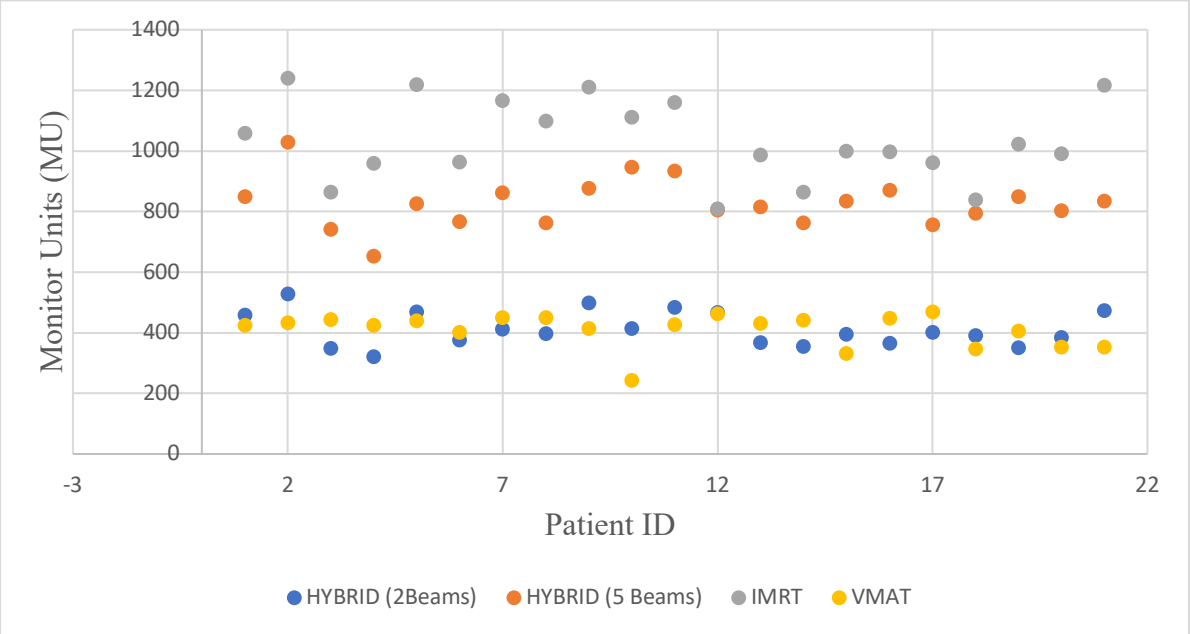

Figure 4.37 Dot plot of monitor units (MU) per 2 Gy of a technique for all Intact Breast cases.

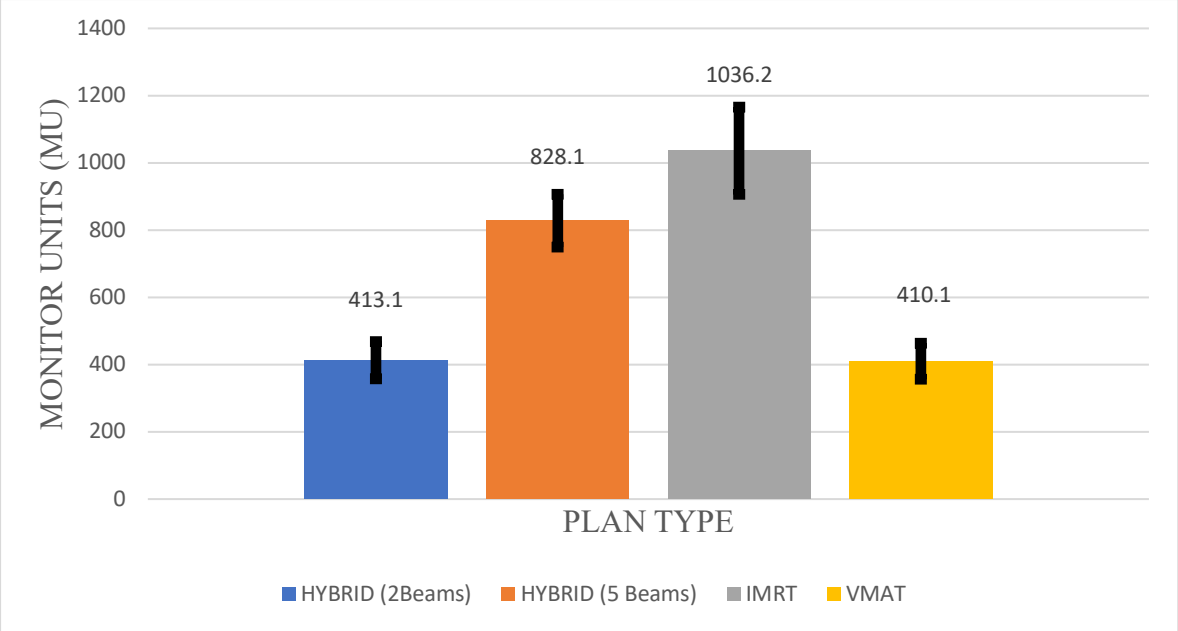

Figure 4.38 Average monitor units (MU) per 2 Gy of a technique for intact breast cases.

In addition to MU, the complexity of radiotherapy plans can be evaluated using complexity metrics, which assess factors like the modulation of beam intensity, the movement of multi-leaf collimators (MLCs), and the overall delivery efficiency. These metrics are essential for understanding the trade-offs between plan quality and delivery efficiency. According to a study by McNiven *et al*. (2010), and further explored in more recent literature (Chiavassa *et al*., 2019) complexity metrics such as the Modulation Complexity Score (MCS) provide valuable insights into the intricacy of radiotherapy plans.

The Hybrid (2 Beams) technique, with its lower MU and simpler beam arrangement, would likely score higher on simplicity-related metrics but lower on MCS due to its limited modulation capabilities. In contrast, the Hybrid (5 Beams) technique, with more beams and higher MUs, would show increased complexity, potentially reflected in a higher MCS. IMRT, with its highly modulated beams, is expected to have the highest complexity scores, as it requires intricate adjustments to the MLCs to achieve the desired dose distribution. This

complexity is a double-edged sword; while it allows for precise targeting, it also increases the potential for delivery errors and requires more sophisticated quality assurance measures.

VMAT, while having fewer MUs than IMRT, would likely demonstrate high complexity metrics due to its dynamic arc delivery, which involves continuous changes in gantry angle, dose rate, and MLC positions. It however has the ability to deliver these complex plans efficiently. wthat VMAT strikes a favourable balance between plan complexity and delivery efficiency. This efficiency is crucial in a clinical setting where treatment time and machine workload are critical considerations.

The variations in MU and plan complexity have significant clinical implications. Techniques requiring higher MUs, such as IMRT and Hybrid (5 Beams), offer enhanced dose conformity but at the cost of increased treatment time and greater potential for machine wear and error. This is particularly critical in intact breast cases, where the higher MU reflects the added complexity of targeting the breast tissue while sparing surrounding organs at risk (OARs).

On the other hand, VMAT's ability to deliver complex plans with fewer MUs highlights its efficiency and potential for widespread clinical adoption, particularly in high-throughput centres. The slightly lower MU in intact breast cases suggests that VMAT may be particularly well-suited for these scenarios, offering a favourable balance between efficiency and complexity. However, the inherent complexity of VMAT plans still necessitates careful planning and verification to ensure safe and effective treatment delivery.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This study aimed to evaluate the superiority of various advanced radiotherapy planning techniques, Hybrid (2 Beams), Hybrid (5 Beams), IMRT, and VMAT in optimising dose distribution, minimising radiation exposure to critical structures, and improving overall treatment outcomes for breast cancer cases. The analysis was divided into two primary scenarios: chest wall irradiation and intact breast irradiation, given the distinct clinical and dosimetric challenges each present. The following were the major findings from the study:

5.1.1 Target Coverage and Dose Homogeneity

VMAT provided superior dose conformity across both scenarios, achieving the lowest conformity index (CI) values, particularly in intact breast cases.

The Hybrid (5 Beams) technique recorded superior homogeneity in both chest-wall and intact breast cases.

5.1.2 Technique Suitability for either Chest Wall or Intact Breast Irradiation

For both chest wall and intact breast irradiation, the Hybrid (5 Beams) technique, was the optimal choice considering the conformity, homogeneity, organ-at-risk sparing, and the number of monitor units.

5.1.3 Toxicity to Organs at Risk

The Hybrid (2 Beams) technique achieved the most significant organ at risk sparing in the contralateral breast, heart, combined lungs, and ipsilateral lungs in both chest wall and intact breast scenarios.

5.1.4 Estimated Delivery Times and Plan Complexity

Hybrid (2 beams) demonstrated a shorter treatment delivery time for the chest-wall case while VMAT demonstrated a shorter treatment delivery time for intact breast cases.

The IMRT technique proved to be the most complex of the plans using the fluence metrics as the means of comparison.

Despite these variations, the results indicate that all the techniques being compared adhered to the principle of radiation therapy by delivering high doses to the PTV while minimising the toxicity to the normal organs as all the various techniques passed their tolerances, ultimately reflecting high-quality treatment plans. The differences observed could be attributed to factors such as sample size, planning strategies, or optimisation algorithms, rather than being determined solely by the radiotherapy techniques being used.

5.2 RECOMMENDATIONS

It is important to recognise that treatment planning results can be affected by factors such as the treatment planning system used, the experience of the planner, the tools and methods employed for comparison, and the patient's anatomical variations. Even with careful attempts to balance these variables across the techniques, their influence cannot be completely ruled out. As a result, some of the findings could be influenced by these confounding factors. Therefore, the following recommendations were made;

The Research Community;

Implement rigorous patient specific quality assurance (PSQA) procedures particularly for complex techniques like IMRT and VMAT, to ensure accurate dose delivery and minimise potential treatment errors.

The Radiation Oncologist and Medical Physicist at the Study site

Tailor the selection of radiotherapy techniques to individual patient anatomy and clinical risks, and prioritise techniques that minimise dose to critical structures in high-risk patients or patients with comorbidities.

5.3 LIMITATIONS

While this study provides valuable insights into the comparative effectiveness of advanced radiotherapy techniques, several limitations must be acknowledged to contextualise the findings.

The study's limited sample size may affect the generalisability of the findings. Future studies with larger and more diverse patient populations are needed to validate these results.

Different treatment planning systems and versions may generate different outcomes, as different calculation models are used.

5.4 FUTURE WORK

Future research should focus on the long-term clinical impacts of different radiotherapy techniques, including their effects on patient survival and quality of life. Incorporating larger sample sizes and evaluating new technological advancements will provide a more comprehensive understanding of the benefits and limitations of various radiotherapy approaches for breast irradiation. Additionally, conducting patient-specific quality assurance (QA) will be crucial in assessing the gamma passing rate for each technique, ensuring that the delivered radiation matches the planned treatment. This approach will not only ascertain the deliverability of each technique but also enhance the reliability of the results, contributing to a more comprehensive understanding of the benefits and limitations of various radiotherapy approaches for breast irradiation.

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APPENDIX

APPENDIX A; ETHICAL CLEARANCE FROM ETHICS COMMITTEE BOARD

UNIVERSITY OF GHANA
ETHICS COMMITTEE FOR BASIC AND APPLIED SCIENCES (ECBAS)
P. O. Box LG 1195, Legon, Accra, Ghana

Ref. No: ECBAS 053/23-24

20th May, 2024

Prosper Amankwah
Department of Medical Physics,
University of Ghana
Legon, Accra

Dear Mr. Amankwah,

ECBAS 053/23-24: DOSIMETRIC COMPARISON BETWEEN HYBRID PLANNING FOR BREAST IRRADIATION

This is to inform you that the above referenced study has been presented to the Ethics Committee for Basic and Applied Sciences for a full board review and the following actions taken subject to the conditions and explanation provided below:

Expiry Date:	25/04/2025
On Agenda for:	Initial Submission
Date of Submission:	26/02/2024
ECBAS Action:	Approved
Reporting:	Annually

Please accept my congratulations.

Yours sincerely,

Professor Dorcas Osei-Safo
ECBAS Chairperson

APPENDIX B; RAW DATA SHEET FOR VARIOUS PLANS

TABLE 1. CHESTWALL PTV DATA SHEET FOR HYBRID 2 BEAMS

PATIENT ID	FIELD_IS	_D2 (Gy)_IS	_D50 (Gy)_IS	_D98 (Gy)_IS	_HI_IS	_TV (cc)_IS	_95% isodose (cc)_IS	_CI_IS	Monitor Units
001	2-OPTIMISED FIELDS	52.09	50.05	48.20	0.078	580.20	828.70	1.428	409
002	2-OPTIMISED FIELDS	51.89	50.00	48.10	0.076	512.30	723.00	1.411	356
003	2-OPTIMISED FIELDS	51.56	50.00	47.89	0.073	401.30	563.10	1.403	340
004	2-OPTIMISED FIELDS	53.14	49.95	47.68	0.109	669.30	1002.60	1.498	396
005	2-OPTIMISED FIELDS	52.15	50.04	48.05	0.082	519.70	748.80	1.441	384
006	2-OPTIMISED FIELDS	53.15	49.90	47.73	0.109	944.80	1419.60	1.503	405
007	2-OPTIMISED FIELDS	53.65	49.98	47.37	0.126	1281.00	1664.00	1.299	381
008	2-OPTIMISED FIELDS	52.10	50.04	48.12	0.080	464.80	662.50	1.425	390
009	2-OPTIMISED FIELDS	51.13	49.80	47.81	0.067	390.30	582.70	1.493	410
010	2-OPTIMISED FIELDS	51.66	50.06	48.21	0.069	681.40	933.10	1.369	383

011	2-OPTIMISED FIELDS	52.73	49.81	47.49	0.105	941.50	1288.30	1.368	404
012	2-OPTIMISED FIELDS	51.64	50.02	48.58	0.061	453.10	712.30	1.572	403
013	2-OPTIMISED FIELDS	52.74	49.69	48.14	0.093	499.00	865.60	1.735	390
014	2-OPTIMISED FIELDS	51.93	50.03	48.47	0.069	301.80	515.60	1.708	386
015	2-OPTIMISED FIELDS	53.73	49.77	47.49	0.125	335.20	743.50	2.218	405
016	2-OPTIMISED FIELDS	53.90	49.88	47.19	0.135	441.50	877.90	1.988	377
017	2-OPTIMISED FIELDS	51.73	50.05	48.05	0.074	745.70	1044.30	1.400	388
018	2-OPTIMISED FIELDS	52.56	50.08	47.73	0.096	859.80	1206.30	1.403	372
019	2-OPTIMISED FIELDS	52.54	50.06	48.04	0.090	845.00	1109.40	1.313	379
020	2-OPTIMISED FIELDS	51.62	50.10	47.86	0.075	701.20	1035.30	1.476	379
021	2-OPTIMISED FIELDS	53.96	49.83	47.40	0.132	629.90	949.20	1.507	400
022	2-OPTIMISED FIELDS	51.52	50.06	48.17	0.067	410.40	646.80	1.576	382
023	2-OPTIMISED FIELDS	51.40	50.06	48.43	0.059	392.40	660.40	1.683	342
024	2-OPTIMISED FIELDS	51.74	50.11	47.98	0.075	435.70	649.30	1.490	427
025	2-OPTIMISED FIELDS	52.31	49.95	48.36	0.079	1006.00	1461.90	1.453	406
026	2-OPTIMISED FIELDS	52.11	50.10	47.69	0.088	496.10	821.60	1.656	412

027	2-OPTIMISED FIELDS	53.04	49.95	47.64	0.108	557.50	929.00	1.666	409
028	2-OPTIMISED FIELDS	53.26	50.16	46.72	0.130	241.70	309.00	1.278	363
029	2-OPTIMISED FIELDS	51.61	50.09	47.93	0.073	676.20	1054.20	1.559	382
MEAN		52.365	49.987	47.880	0.090	600.510	896.828	1.528	388.275
STANDARD DEVIATION		0.802	0.114	0.404	0.023	236.384	300.240	0.198	20.200

TABLE 2. CHESTWALL PTV DATA SHEET FOR HYBRID 5 BEAMS

PATIENT ID	**FIELD_IS**	**_D2 (Gy)_IS**	**_D50 (Gy)_IS**	**_D98 (Gy)_IS**	**_HI_IS**	**_TV (cc)_IS**	**_95% isodose (cc)_IS**	**_CI_IS**	**Monitor Units**
001	5-OPTIMISED FIELDS	51.50	49.90	48.86	0.053	585.60	786.10	1.342	773
002	5-OPTIMISED FIELDS	51.64	49.90	48.73	0.058	512.30	672.70	1.313	697
003	5-OPTIMISED FIELDS	51.30	50.04	48.58	0.054	401.30	551.60	1.375	725
004	5-OPTIMISED FIELDS	51.67	49.96	48.50	0.064	669.30	918.20	1.372	896

005	5-OPTIMISED FIELDS	51.40	49.98	48.74	0.053	519.70	667.10	1.284	592
006	5-OPTIMISED FIELDS	51.41	49.99	48.59	0.056	944.80	1194.70	1.265	853
007	5-OPTIMISED FIELDS	51.90	49.92	48.47	0.069	1281.00	1534.40	1.198	826
008	5-OPTIMISED FIELDS	51.59	49.91	48.55	0.061	464.80	571.50	1.230	687
009	5-OPTIMISED FIELDS	51.90	50.25	48.53	0.067	390.30	524.60	1.344	623
010	5-OPTIMISED FIELDS	51.49	50.07	48.28	0.064	681.40	847.10	1.243	796
011	5-OPTIMISED FIELDS	51.55	49.96	48.61	0.059	941.50	1190.50	1.264	795
012	5-OPTIMISED FIELDS	51.19	49.95	48.83	0.047	453.10	599.20	1.322	747
013	5-OPTIMISED FIELDS	51.90	49.87	48.80	0.062	499.00	680.50	1.364	782
014	5-OPTIMISED FIELDS	51.67	50.26	49.04	0.052	301.80	434.90	1.441	739
015	5-OPTIMISED FIELDS	51.76	49.96	48.45	0.066	335.20	471.30	1.406	648
016	2-OPTIMISED FIELDS	51.22	49.80	47.07	0.144	441.50	752.30	1.704	467
017	2-OPTIMISED FIELDS	51.43	49.95	48.78	0.053	745.70	903.40	1.211	746
018	2-OPTIMISED FIELDS	51.64	49.95	48.53	0.062	859.80	1102.60	1.282	763
019	2-OPTIMISED FIELDS	51.50	49.92	48.64	0.057	845.00	1033.40	1.223	773
020	2-OPTIMISED FIELDS	51.38	50.00	48.54	0.057	701.20	898.80	1.282	751

021	2-OPTIMISED FIELDS	51.99	50.00	48.18	0.076	628.90	758.20	1.206	686
022	2-OPTIMISED FIELDS	51.50	49.96	48.66	0.057	410.40	531.50	1.295	724
023	2-OPTIMISED FIELDS	51.33	49.92	48.00	0.067	392.40	574.20	1.463	662
024	2-OPTIMISED FIELDS	51.32	49.99	48.81	0.050	435.70	585.70	1.344	750
025	2-OPTIMISED FIELDS	51.47	49.95	48.93	0.051	1006.00	1315.60	1.308	689
026	2-OPTIMISED FIELDS	51.73	50.00	48.32	0.068	496.10	700.50	1.412	719
027	2-OPTIMISED FIELDS	51.57	49.94	48.25	0.066	557.50	733.80	1.316	730
028	2-OPTIMISED FIELDS	51.58	50.00	48.39	0.064	241.70	308.90	1.278	732
029	2-OPTIMISED FIELDS	51.75	50.07	48.04	0.074	676.20	906.20	1.340	771
MEAN		51.56	49.978	48.507	0.061	600.662	784.466	1.325	729.0345
STANDARD DEVIATION		0.521	0.093	0.368	0.008	236.366	278.461	0.099	80.69632

TABLE 3. CHESTWALL PTV DATA SHEET FOR IMRT

PATIENT ID	FIELD_IS	_D2 (Gy)_IS	_D50 (Gy)_IS	_D98 (Gy)_IS	_HI_IS	_TV (cc)_IS	_95% isodose (cc)_IS	_CI_IS	Monitor Units
001	5-OPTIMISED FIELDS	51.45	50.00	48.22	0.065	585.60	702.10	1.199	891
002	5-OPTIMISED FIELDS	52.51	49.89	48.08	0.089	512.30	593.30	1.158	904
003	5-OPTIMISED FIELDS	51.52	50.05	48.47	0.061	401.30	499.70	1.245	985
004	5-OPTIMISED FIELDS	51.27	49.99	48.72	0.051	669.30	810.80	1.211	1097
005	5-OPTIMISED FIELDS	51.64	49.96	48.53	0.062	519.70	637.00	1.226	970
006	5-OPTIMISED FIELDS	51.96	49.89	48.43	0.071	944.80	1117.80	1.183	1185
007	5-OPTIMISED FIELDS	51.59	49.93	48.63	0.059	1281.00	1422.70	1.111	1118
008	5-OPTIMISED FIELDS	52.50	49.91	48.32	0.084	435.30	517.50	1.189	898
009	5-OPTIMISED FIELDS	52.22	50.02	47.44	0.096	390.30	454.40	1.164	922
010	5-OPTIMISED FIELDS	51.78	50.03	47.95	0.077	681.40	807.90	1.186	1042
011	5-OPTIMISED FIELDS	52.47	49.92	47.90	0.092	941.50	1111.80	1.181	972

012	5-OPTIMISED FIELDS	51.56	49.93	48.61	0.059	453.10	552.00	1.218	822
013	5-OPTIMISED FIELDS	51.85	49.96	49.59	0.045	499.00	623.90	1.250	1014
014	5-OPTIMISED FIELDS	51.56	50.05	47.78	0.076	301.80	367.30	1.217	828
015	5-OPTIMISED FIELDS	50.78	50.03	49.05	0.035	335.20	413.70	1.234	762
016	5-OPTIMISED FIELDS	51.62	49.96	48.08	0.071	441.50	505.90	1.146	886
017	5-OPTIMISED FIELDS	51.90	49.93	48.51	0.068	745.70	880.00	1.180	991
018	5-OPTIMISED FIELDS	52.49	49.86	48.17	0.087	859.80	984.30	1.145	931
019	5-OPTIMISED FIELDS	51.24	49.82	48.71	0.051	845.00	967.80	1.145	935
020	5-OPTIMISED FIELDS	51.86	49.97	48.32	0.071	700.20	829.10	1.184	1029
021	5-OPTIMISED FIELDS	52.80	49.80	48.17	0.093	629.90	728.20	1.156	989
022	5-OPTIMISED FIELDS	52.09	49.91	48.32	0.076	410.40	488.70	1.191	879
023	5-OPTIMISED FIELDS	51.65	50.23	49.10	0.051	392.40	554.70	1.414	914
024	5-OPTIMISED FIELDS	51.67	49.96	48.47	0.064	435.70	547.20	1.256	954
025	5-OPTIMISED FIELDS	51.82	49.91	48.60	0.065	1006.00	1184.60	1.178	867
026	5-OPTIMISED FIELDS	53.12	49.82	48.17	0.099	496.10	617.90	1.246	916
027	5-OPTIMISED FIELDS	51.65	50.21	48.89	0.055	557.50	678.30	1.217	917

028	5-OPTIMISED FIELDS	52.56	49.89	48.10	0.089	241.70	293.70	1.215	966
029	5-OPTIMISED FIELDS	52.40	49.89	47.68	0.095	676.20	741.40	1.096	940
MEAN		51.915	49.956	48.380	0.071	599.645	711.507	1.198	949.103
STANDARD DEVIATION		0.513	0.097	0.444	0.017	237.001	262.218	0.057	88.155

TABLE 4. CHESTWALL PTV DATA SHEET FOR VMAT

PATIENT ID	**FIELD_IS**	**_D2 (Gy)_IS**	**_D50 (Gy)_IS**	**_D98 (Gy)_IS**	**_HI_**	**_TV (cc)_IS**	**_95% isodose (cc)_IS**	**_CI_IS**	**Monitor Units**
001	2-Half Arcs	52.11	50.11	46.58	0.110	585.60	617.60	1.055	427
002	2-Half Arcs	52.37	50.01	47.39	0.100	512.30	548.40	1.070	440
003	2-Half Arcs	52.41	50.11	46.91	0.110	401.30	437.30	1.090	423
004	2-Half Arcs	52.57	50.02	47.15	0.108	669.30	692.50	1.035	340
005	2-Half Arcs	52.48	50.10	46.39	0.122	519.70	546.70	1.052	482

006	2-Half Arcs	52.81	49.97	47.19	0.112	944.80	1000.00	1.058	450
007	2-Half Arcs	52.95	49.99	46.68	0.125	1281.00	1298.50	1.014	435
008	2-Half Arcs	52.09	50.02	47.69	0.088	435.30	481.90	1.107	490
009	2-Half Arcs	52.28	50.09	47.02	0.105	390.30	420.30	1.077	494
010	2-Half Arcs	52.84	50.06	46.81	0.120	681.40	733.00	1.076	369
011	2-Half Arcs	53.09	49.96	46.90	0.124	941.50	1014.40	1.077	406
012	2-Half Arcs	52.05	50.04	47.14	0.098	453.10	506.30	1.117	459
013	2-Half Arcs	52.41	49.98	47.53	0.098	499.00	544.00	1.090	470
014	2-Half Arcs	52.01	50.09	46.91	0.102	301.80	334.70	1.109	455
015	2-Half Arcs	52.00	50.03	47.57	0.089	335.20	357.40	1.066	437
016	2-Half Arcs	52.18	49.99	47.38	0.096	441.50	462.60	1.048	487
017	2-Half Arcs	52.36	49.99	47.43	0.099	745.70	774.60	1.039	450
018	2-Half Arcs	53.18	50.07	46.49	0.134	859.80	864.70	1.006	408
019	2-Half Arcs	52.17	50.00	47.62	0.091	845.00	881.10	1.043	444
020	2-Half Arcs	52.22	50.14	46.83	0.107	700.20	753.80	1.077	426
021	2-Half Arcs	52.10	50.09	47.01	0.102	730.33	750.20	1.027	453

022	2-Half Arcs	52.07	50.04	47.69	0.088	410.40	447.40	1.090	501
023	2-Half Arcs	51.92	50.06	47.54	0.087	392.40	440.30	1.122	474
024	2-Half Arcs	52.14	50.02	47.56	0.092	435.70	471.10	1.081	451
025	2-Half Arcs	52.22	50.06	47.41	0.096	1006.00	1056.10	1.050	366
026	2-Half Arcs	52.84	50.18	46.28	0.131	496.10	483.80	0.975	352
027	2-Half Arcs	52.31	50.00	47.46	0.097	557.50	579.90	1.040	412
028	2-Half Arcs	51.93	50.19	46.65	0.105	241.70	265.70	1.099	454
029	2-Half Arcs	52.73	50.15	46.31	0.128	676.20	694.80	1.028	349
MEAN		52.374	50.054	47.087	0.106	598.564	632.461	1.063	434.621
STANDARD DEVIATION		0.352	0.061	0.431	0.014	241.126	243.943	0.034	43.868

TABLE 5. CHESTWALL OAR DATA SHEET FOR HYBRID 2 BEAMS

PATIENT ID	FIELD_IS	HEART_D40_IS	HEART_D20_IS	IPSILATERAL LUNG_D45_IS	IPSILATERAL LUNG_D35_IS	WHOLE LUNG_D25_IS	WHOLE LUNG_D20_IS	CONTRA BREAST
001	2-OPTIMISED FIELDS	0.38	0.75	2.56	3.90	2.58	3.73	
002	2-OPTIMISED FIELDS	0.72	1.28	3.18	5.69	3.08	5.03	
003	2-OPTIMISED FIELDS	0.72	1.26	4.75	7.03	4.47	10.00	
004	2-OPTIMISED FIELDS	0.72	1.27	2.55	4.01	2.42	3.66	
005	2-OPTIMISED FIELDS	0.47	0.92	2.23	3.13	2.25	3.47	0.
006	2-OPTIMISED FIELDS	1.06	2.01	3.26	5.35	3.54	5.53	
007	2-OPTIMISED FIELDS	0.74	1.37	3.25	4.80	2.76	3.90	
008	2-OPTIMISED FIELDS	0.50	0.96	2.56	3.97	2.91	4.29	
009	2-OPTIMISED FIELDS	1.23	2.10	3.15	9.61	3.56	9.84	
010	2-OPTIMISED FIELDS	1.42	2.36	3.62	9.91	3.42	7.09	
011	2-OPTIMISED FIELDS	1.07	2.11	2.47	3.56	2.52	3.46	
012	2-OPTIMISED FIELDS	0.30	0.62	2.72	4.15	2.91	4.29	

013	2-OPTIMISED FIELDS	0.38	0.78	2.72	4.31	3.18	4.90	
014	2-OPTIMISED FIELDS	0.33	0.69	2.43	2.52	1.75	2.36	
015	2-OPTIMISED FIELDS	0.97	1.95	1.96	2.81	1.70	2.24	
016	2-OPTIMISED FIELDS	1.14	2.47	2.54	3.73	1.80	2.51	
017	2-OPTIMISED FIELDS	1.59	4.20	2.80	4.27	2.12	2.96	0.
018	2-OPTIMISED FIELDS	2.02	12.43	3.76	6.63	2.74	3.95	O.
019	2-OPTIMISED FIELDS	0.92	2.14	2.68	4.01	1.98	2.75	0.
020	2-OPTIMISED FIELDS	1.00	2.25	4.03	7.51	2.96	4.69	
021	2-OPTIMISED FIELDS	1.86	7.93	3.23	5.36	2.03	2.88	
022	2-OPTIMISED FIELDS	0.96	2.03	3.81	9.01	2.39	4.28	
023	2-OPTIMISED FIELDS	1.19	2.96	2.60	4.44	1.83	2.70	0.
024	2-OPTIMISED FIELDS	1.30	2.94	1.80	2.59	1.26	1.74	0.
025	2-OPTIMISED FIELDS	1.71	4.16	3.06	4.25	2.17	2.91	
026	2-OPTIMISED FIELDS	2.48	2.70	2.51	3.94	1.71	2.28	
027	2-OPTIMISED FIELDS	1.48	4.68	2.92	4.30	2.27	3.04	0.
028	2-OPTIMISED FIELDS	0.69	1.46	2.07	3.54	1.14	1.78	0.

029	2-OPTIMISED FIELDS	2.06	1.98	6.18	3.52	2.01	3.02	0.
MEAN		1.087	2.578	3.013	4.891	2.464	3.975	0.3
STANDARD DEVIATION		0.557	2.85	0.875	1.962	0.734	1.991	0.0

TABLE 6. CHESTWALL OAR DATA SHEET FOR HYBRID 5 BEAMS

PATIENT ID	FIELD_IS	HEART_D40_IS	HEART_D20_IS	IPSILATERAL LUNG_D45_IS	IPSILATERAL LUNG_D35_IS	WHOLE LUNG_D25_IS	WHOLE LUNG_D20_IS	CONTRAL BREAST
001	5-OPTIMISED FIELDS	1.47	2.22	8.40	10.27	8.43	10.00	
002	5-OPTIMISED FIELDS	1.91	2.96	6.74	9.82	6.65	9.07	
003	5-OPTIMISED FIELDS	1.84	2.42	6.80	13.70	6.53	11.59	
004	5-OPTIMISED FIELDS	2.28	3.22	8.59	10.90	8.35	10.22	
005	5-OPTIMISED FIELDS	2.27	4.46	10.79	12.40	11.36	12.87	1.
006	5-OPTIMISED FIELDS	2.35	4.31	10.18	12.81	10.58	13.09	
007	5-OPTIMISED FIELDS	2.07	3.38	9.01	11.59	8.17	10.14	

008	5-OPTIMISED FIELDS	1.87	4.24	8.04	10.55	8.63	11.14	
009	5-OPTIMISED FIELDS	2.44	3.83	6.86	13.32	7.35	13.24	
010	5-OPTIMISED FIELDS	2.48	3.51	7.04	13.00	6.70	10.80	
011	5-OPTIMISED FIELDS	1.98	3.21	8.65	10.20	8.71	10.07	
012	5-OPTIMISED FIELDS	1.44	2.44	8.47	10.67	8.82	10.78	
013	5-OPTIMISED FIELDS	1.67	3.17	7.78	10.83	8.59	11.64	
014	5-OPTIMISED FIELDS	1.40	2.22	5.01	7.01	5.03	6.65	
015	5-OPTIMISED FIELDS	2.03	4.66	6.44	8.74	5.50	7.18	
016	5-OPTIMISED FIELDS	2.10	4.07	5.21	6.68	3.98	5.12	
017	5-OPTIMISED FIELDS	2.83	6.20	9.46	11.57	8.16	9.60	1.0
018	5-OPTIMISED FIELDS	3.76	14.01	10.07	13.72	8.38	10.39	0.3
019	5-OPTIMISED FIELDS	3.09	5.76	8.92	11.43	7.20	9.06	1.3
020	5-OPTIMISED FIELDS	3.52	6.34	11.40	15.05	9.28	12.30	
021	5-OPTIMISED FIELDS	2.97	11.81	8.37	11.15	5.87	7.67	
022	5-OPTIMISED FIELDS	2.33	3.90	9.10	14.79	6.91	9.71	
023	5-OPTIMISED FIELDS	2.62	5.50	7.31	10.07	5.88	7.48	1.3

024	5-OPTIMISED FIELDS	2.83	5.25	7.88	9.49	6.30	7.77	1.
025	5-OPTIMISED FIELDS	2.66	6.31	9.64	11.31	8.23	9.48	
026	5-OPTIMISED FIELDS	3.26	8.56	6.54	8.55	3.97	5.92	
027	5-OPTIMISED FIELDS	2.63	7.26	10.21	12.10	8.99	10.45	1.
028	5-OPTIMISED FIELDS	2.13	3.40	8.52	10.72	6.38	8.03	2.
029	5-OPTIMISED FIELDS	3.05	10.42	8.73	12.56	6.11	10.56	0.
MEAN		2.389	5.139	8.281	11.207	7.415	9.725	1.2
STANDARD DEVIATION		0.599	2.846	1.532	1.994	1.729	2.055	0.4

TABLE 7. CHESTWALL OAR DATA SHEET FOR IMRT

PATIENT ID	FIELD_IS	HEART_D40_IS	HEART_D20_IS	IPSILATERAL LUNG_D45_IS	IPSILATERAL LUNG_D35_IS	WHOLE LUNG_D25_IS	WHOLE LUNG_D20_IS	CONTRAL BREAST
001	5-OPTIMISED FIELDS	1.89	3.09	9.97	12.55	10.79	13.17	
002	5-OPTIMISED FIELDS	2.78	4.45	9.77	13.17	12.06	14.62	
003	5-OPTIMISED FIELDS	2.38	3.53	10.16	13.63	10.01	12.90	4.2
004	5-OPTIMISED FIELDS	2.16	3.31	11.22	13.16	13.26	11.62	3.2
005	5-OPTIMISED FIELDS	2.81	6.07	7.70	9.57	8.92	10.94	6.1
006	5-OPTIMISED FIELDS	2.59	3.80	9.70	12.09	10.64	12.85	
007	5-OPTIMISED FIELDS	2.26	3.18	8.63	12.23	9.85	12.21	5.3
008	5-OPTIMISED FIELDS	2.52	6.34	8.40	11.60	10.42	13.67	
009	5-OPTIMISED FIELDS	2.80	5.01	8.75	13.45	9.45	13.69	
010	5-OPTIMISED FIELDS	2.79	3.84	8.85	12.95	9.28	12.15	
011	5-OPTIMISED FIELDS	2.98	5.25	10.44	12.71	10.84	12.63	
012	5-OPTIMISED FIELDS	1.86	2.83	8.94	12.08	10.89	13.47	

013	5-OPTIMISED FIELDS	1.94	3.65	7.94	12.34	9.39	13.76	
014	5-OPTIMISED FIELDS	1.86	3.23	5.83	8.37	7.74	9.38	
015	5-OPTIMISED FIELDS	2.57	10.77	11.35	13.70	11.12	12.84	
016	5-OPTIMISED FIELDS	2.81	9.74	10.70	12.44	9.65	10.96	
017	5-OPTIMISED FIELDS	3.15	7.21	12.32	14.99	10.61	12.65	
018	5-OPTIMISED FIELDS	4.02	12.86	11.78	15.01	9.82	12.11	2.(
019	5-OPTIMISED FIELDS	2.99	6.54	9.78	11.71	7.97	9.90	3.3
020	5-OPTIMISED FIELDS	3.05	7.81	11.88	15.07	9.97	12.72	
021	5-OPTIMISED FIELDS	3.43	9.62	11.04	13.96	8.31	10.37	
022	5-OPTIMISED FIELDS	2.88	5.91	12.18	16.66	9.85	12.89	
023	5-OPTIMISED FIELDS	2.55	5.80	9.23	11.85	7.60	9.46	3.9
024	5-OPTIMISED FIELDS	2.64	5.10	10.88	13.52	7.77	10.66	1.3
025	5-OPTIMISED FIELDS	3.51	8.28	12.34	14.43	10.48	12.09	
026	5-OPTIMISED FIELDS	3.77	14.47	10.56	13.07	6.45	9.69	
027	5-OPTIMISED FIELDS	2.30	6.52	13.99	15.92	12.15	14.32	4.3
028	5-OPTIMISED FIELDS	1.99	3.35	11.22	13.50	9.19	10.90	2.9

029	5-OPTIMISED FIELDS	3.16	7.14	14.56	18.80	12.93	15.64	4.6
MEAN		2.705	6.162	10.349	13.260	9.911	12.216	3.9
STANDARD DEVIATION		0.552	2.960	1.851	1.965	1.565	1.575	1.2

TABLE 8. CHESTWALL OAR DATA SHEET FOR VMAT

PATIENT ID	FIELD_IS	HEART_D40_IS	HEART_D20_IS	IPSILATERAL LUNG_D45_IS	IPSILATERAL LUNG_D35_IS	WHOLE LUNG_D25_IS	WHOLE LUNG_D20_IS	CONTRAL BREAST
001	2 HALF ARCS	2.88	6.56	14.07	17.87	14.37	7.52	3.8
002	2 HALF ARCS	3.42	7.71	13.32	17.53	14.50	17.69	
003	2 HALF ARCS	3.40	7.95	14.19	18.84	14.11	17.91	3.8
004	2 HALF ARCS	2.79	6.95	13.63	17.43	13.58	16.66	4.3
005	2 HALF ARCS	3.75	15.19	11.62	15.19	12.70	16.47	3.1
006	2 HALF ARCS	4.16	8.71	12.21	16.74	13.05	17.20	
007	2 HALF ARCS	4.03	9.39	13.75	18.26	13.60	16.30	3.4

008	2 HALF ARCS	3.78	10.65	10.46	15.25	12.18	16.58	
009	2 HALF ARCS	3.81	8.36	9.99	16.54	11.98	17.67	
010	2 HALF ARCS	3.50	7.34	11.96	18.32	13.10	17.96	
011	2 HALF ARCS	3.27	7.93	12.42	15.82	12.56	15.56	
012	2 HALF ARCS	2.77	7.68	11.32	15.42	13.11	16.36	
013	2 HALF ARCS	2.75	8.08	10.31	14.55	11.43	16.09	
014	2 HALF ARCS	3.48	7.88	10.24	13.51	13.08	10.61	
015	2 HALF ARCS	2.80	11.63	10.26	13.17	10.85	12.56	
016	2 HALF ARCS	3.52	9.81	11.58	15.50	12.03	14.03	
017	2 HALF ARCS	4.11	13.84	11.86	16.47	10.50	13.05	4.
018	2 HALF ARCS	4.44	18.77	12.29	18.51	9.35	12.92	3.
019	2 HALF ARCS	3.88	14.62	11.80	16.96	9.60	12.05	3.
020	2 HALF ARCS	4.22	11.30	13.41	18.87	11.03	14.78	
021	2 HALF ARCS	3.65	10.02	11.05	19.50	10.01	11.32	
022	2 HALF ARCS	3.87	9.79	11.43	16.80	10.48	13.24	
023	2 HALF ARCS	4.02	16.21	11.34	15.93	9.41	12.03	2.

024	2 HALF ARCS	4.01	15.49	11.27	15.69	9.51	11.79	2.2
025	2 HALF ARCS	3.65	12.19	16.91	20.94	13.75	16.45	
026	2 HALF ARCS	3.85	18.31	9.99	16.62	6.84	9.52	
027	2 HALF ARCS	3.33	11.44	15.22	19.03	13.09	15.79	4.8
028	2 HALF ARCS	3.39	10.03	15.44	19.22	12.77	15.25	4.3
029	2 HALF ARCS	4.36	18.84	19.96	25.08	17.48	21.49	2.3
MEAN		3.617	11.127	12.528	17.226	12.071	14.719	3.5
STANDARD DEVIATION		0.478	3.672	2.220	2.329	2.077	2.973	0.7

TABLE 9. INTACT BREAST PTV DATA SHEET FOR HYBRID 2 BEAMS

PATIENT ID	FIELD_IS	_D2 (Gy)_IS	_D50 (Gy)_IS	_D98 (Gy)_IS	_HI_IS	_TV (cc)_IS	_95% isodose (cc)_IS	_CI_IS	Monitor Units
001	2-OPTIMISED FIELDS	52.80	50.08	46.70	0.122	1172.10	1429.80	1.220	459
002	2-OPTIMISED FIELDS	51.00	50.17	47.14	0.077	1902.50	1977.70	1.040	529
003	2-OPTIMISED FIELDS	51.77	50.11	48.22	0.071	863.80	1096.10	1.269	349
004	2-OPTIMISED FIELDS	51.43	50.16	47.41	0.080	840.90	983.20	1.169	322
005	2-OPTIMISED FIELDS	51.71	50.13	47.83	0.077	1710.10	1836.50	1.074	469
006	2-OPTIMISED FIELDS	51.23	50.10	47.79	0.069	658.40	818.00	1.242	378
007	2-OPTIMISED FIELDS	53.18	49.93	47.76	0.109	1362.00	2013.50	1.478	412
008	2-OPTIMISED FIELDS	51.77	50.60	48.07	0.073	517.20	712.60	1.378	399
009	2-OPTIMISED FIELDS	52.89	50.10	47.56	0.106	1440.30	1843.30	1.280	500
010	2-OPTIMISED FIELDS	54.03	49.83	47.39	0.133	1854.80	2204.80	1.189	415
011	2-OPTIMISED FIELDS	53.21	50.00	47.63	0.112	1936.80	2260.90	1.167	484

012	2-OPTIMISED FIELDS	51.39	50.17	47.68	0.074	941.30	1161.60	1.234	467
013	2-OPTIMISED FIELDS	52.14	50.15	47.07	0.101	1199.60	1386.40	1.156	369
014	2-OPTIMISED FIELDS	51.75	50.42	47.39	0.086	496.30	657.90	1.326	355
015	2-OPTIMISED FIELDS	51.45	50.21	47.78	0.073	1032.50	1174.60	1.138	397
016	2-OPTIMISED FIELDS	52.34	50.05	47.55	0.096	1237.00	1496.10	1.209	367
017	2-OPTIMISED FIELDS	52.24	50.25	45.93	0.126	551.30	635.30	1.152	402
018	2-OPTIMISED FIELDS	51.43	50.30	47.00	0.088	917.80	1037.80	1.131	392
019	2-OPTIMISED FIELDS	51.66	50.05	48.04	0.072	1338.60	1580.50	1.181	351
020	2-OPTIMISED FIELDS	51.38	50.09	48.29	0.062	1331.70	1668.80	1.253	385
021	2-OPTIMISED FIELDS	52.10	50.19	47.09	0.100	1110.50	1410.70	1.270	474
MEAN		52.043	50.147	47.492	0.091	1162.643	1399.338	1.217	413.0952
STANDARD DEVIATION		0.764	0.158	0.536	0.020	431.988	490.524	0.097	55.47192

TABLE 10. INTACT BREAST PTV DATA SHEET FOR HYBRID 5 BEAMS

PATIENT ID	FIELD_IS	_D2 (Gy)_IS	_D50 (Gy)_IS	_D98 (Gy)_IS	_HI_IS	_TV (cc)_IS	_95% isodose (cc)_IS	_CI_IS	Monitor Units
001	5-OPTIMISED FIELDS	51.80	49.90	48.50	0.066	1172.10	1379.80	1.177	850
002	5-OPTIMISED FIELDS	51.50	49.97	48.60	0.058	1902.50	2076.10	1.091	1029
003	5-OPTIMISED FIELDS	51.63	49.90	48.80	0.057	863.80	1067.60	1.236	742
004	5-OPTIMISED FIELDS	51.07	50.00	48.59	0.050	840.90	995.40	1.184	654
005	5-OPTIMISED FIELDS	51.10	49.98	48.89	0.044	1710.10	1894.60	1.108	828
006	5-OPTIMISED FIELDS	51.00	49.99	48.98	0.040	658.40	819.90	1.245	767
007	5-OPTIMISED FIELDS	52.07	49.85	48.51	0.071	1362.00	1667.70	1.224	863
008	5-OPTIMISED FIELDS	51.17	50.00	48.79	0.048	517.20	651.40	1.259	764
009	5-OPTIMISED FIELDS	52.15	49.86	48.50	0.073	1440.30	1742.40	1.210	877
010	5-OPTIMISED FIELDS	51.37	49.87	49.02	0.047	1854.80	2238.00	1.207	947
011	5-OPTIMISED FIELDS	51.80	49.90	48.47	0.067	1936.80	2204.60	1.138	935

012	5-OPTIMISED FIELDS	52.75	50.29	48.82	0.078	941.30	1154.10	1.226	805
013	5-OPTIMISED FIELDS	52.22	49.90	48.30	0.079	1199.60	1299.90	1.084	817
014	5-OPTIMISED FIELDS	51.33	49.96	48.90	0.049	496.30	647.60	1.305	763
015	5-OPTIMISED FIELDS	51.82	49.86	48.66	0.063	1032.50	1224.90	1.186	836
016	5-OPTIMISED FIELDS	52.05	50.23	48.63	0.068	1237.00	1416.80	1.145	871
017	5-OPTIMISED FIELDS	51.69	50.00	48.51	0.064	551.30	648.90	1.177	757
018	5-OPTIMISED FIELDS	51.89	49.94	48.50	0.068	917.80	1062.30	1.157	795
019	5-OPTIMISED FIELDS	51.38	49.97	48.98	0.048	1338.60	1575.40	1.177	851
020	5-OPTIMISED FIELDS	51.30	50.00	48.78	0.050	1331.70	1614.50	1.212	803
021	5-OPTIMISED FIELDS	51.69	49.97	48.25	0.069	1110.50	1291.80	1.163	836
MEAN		51.656	49.969	48.666	0.060	1162.643	1365.414	1.186	828.0952
STANDARD DEVIATION		0.433	0.108	0.217	0.011	431.988	479.130	0.054	78.60262

TABLE 11. INTACT BREAST PTV DATA SHEET FOR IMRT

PATIENT ID	FIELD_IS	_D2 (Gy)_IS	_D50 (Gy)_IS	_D98 (Gy)_IS	_HI_IS	_TV (cc)_IS	_95% isodose (cc)_IS	_CI_IS	Monitor Units
001	5-OPTIMISED FIELDS	51.39	49.97	48.78	0.052	1172.10	1305.80	1.114	1060
002	5-OPTIMISED FIELDS	51.73	50.04	48.02	0.074	1902.50	2011.30	1.057	1242
003	5-OPTIMISED FIELDS	51.71	49.92	48.21	0.070	863.80	958.20	1.109	865
004	5-OPTIMISED FIELDS	51.25	50.00	48.65	0.052	840.90	940.80	1.119	960
005	5-OPTIMISED FIELDS	51.26	49.95	48.83	0.049	1710.10	1873.30	1.095	1220
006	5-OPTIMISED FIELDS	51.38	49.95	48.92	0.049	658.40	774.30	1.176	965
007	5-OPTIMISED FIELDS	51.99	49.85	48.51	0.070	1362.00	1510.70	1.109	1168
008	5-OPTIMISED FIELDS	51.60	49.94	48.68	0.058	517.20	619.80	1.198	1099
009	5-OPTIMISED FIELDS	51.32	49.99	48.69	0.053	1440.30	1657.70	1.151	1211
010	5-OPTIMISED FIELDS	51.53	49.95	48.58	0.059	1854.80	2094.70	1.129	1113
011	5-OPTIMISED FIELDS	51.41	50.04	48.35	0.061	1936.80	2090.70	1.079	1160

012	5-OPTIMISED FIELDS	51.81	49.96	48.36	0.069	941.30	1096.40	1.165	811
013	5-OPTIMISED FIELDS	51.80	50.05	47.58	0.084	1199.60	1238.80	1.033	988
014	5-OPTIMISED FIELDS	51.43	49.98	48.67	0.055	496.30	593.80	1.196	865
015	5-OPTIMISED FIELDS	51.56	49.98	48.52	0.061	1032.50	1152.20	1.116	1000
016	5-OPTIMISED FIELDS	52.56	49.85	48.21	0.087	1237.00	1340.50	1.084	999
017	5-OPTIMISED FIELDS	52.18	49.91	48.54	0.073	551.30	617.60	1.120	963
018	5-OPTIMISED FIELDS	51.88	49.94	47.77	0.082	917.80	1001.20	1.091	840
019	5-OPTIMISED FIELDS	51.96	49.88	48.40	0.071	1338.60	1450.70	1.084	1023
020	5-OPTIMISED FIELDS	51.79	49.93	48.47	0.066	1331.70	1512.50	1.136	992
021	5-OPTIMISED FIELDS	51.87	49.84	48.42	0.069	1110.50	1243.90	1.120	1217
MEAN		51.686	49.949	48.436	0.065	1162.643	1289.757	1.118	1036.238
STANDARD DEVIATION		0.321	0.059	0.327	0.011	431.988	459.803	0.041	129.779

TABLE 12. INTACT BREAST PTV DATA SHEET FOR VMAT

PATIENT ID	FIELD_IS	_D2 (Gy)_IS	_D50 (Gy)_IS	_D98 (Gy)_IS	_HI_IS	_TV (cc)_IS	_95% isodose (cc)_IS	_CI_IS	Monitor Units
001	2-HALF-ARCS	51.86	50.13	46.78	0.101	1172.10	1159.40	0.989	425
002	2-HALF-ARCS	52.35	49.97	47.55	0.096	1902.50	1960.50	1.030	434
003	2-HALF-ARCS	52.16	49.97	47.78	0.088	863.80	908.80	1.052	445
004	2-HALF-ARCS	52.12	50.02	47.36	0.095	840.90	878.10	1.044	426
005	2-HALF-ARCS	52.29	49.99	47.46	0.097	1710.10	1737.50	1.016	440
006	2-HALF-ARCS	51.90	50.07	47.25	0.093	658.40	697.50	1.059	402
007	2-HALF-ARCS	52.62	50.09	46.59	0.120	1362.00	1337.10	0.982	451
008	2-HALF-ARCS	51.96	50.07	47.28	0.093	517.20	550.80	1.065	451
009	2-HALF-ARCS	52.09	49.99	47.87	0.084	1440.30	1525.90	1.059	416
010	2-HALF-ARCS	52.06	50.01	47.46	0.092	1854.80	1943.90	1.048	244
011	2-HALF-ARCS	52.08	50.01	47.50	0.092	1936.80	1428.33	0.737	428

012	2-HALF-ARCS	51.91	50.02	47.68	0.085	941.30	976.40	1.037	463
013	2-HALF-ARCS	53.21	49.93	46.88	0.127	1199.60	1193.10	0.995	433
014	2-HALF-ARCS	52.29	49.92	47.30	0.100	496.30	510.20	1.028	443
015	2-HALF-ARCS	52.94	50.64	47.99	0.098	1032.50	1085.10	1.051	332
016	2-HALF-ARCS	53.27	50.24	45.55	0.154	1237.00	1125.20	0.910	448
017	2-HALF-ARCS	52.73	49.98	46.92	0.116	551.30	552.50	1.002	470
018	2-HALF-ARCS	52.72	49.92	47.46	0.105	917.80	951.80	1.037	348
019	2-HALF-ARCS	52.86	50.06	46.57	0.126	1338.60	1309.60	0.978	407
020	2-HALF-ARCS	52.19	50.10	46.98	0.104	1331.70	1337.80	1.005	353
021	2-HALF-ARCS	52.45	50.04	46.95	0.110	1110.50	1105.80	0.996	353
MEAN		52.384	50.056	47.198	0.104	1162.643	1155.968	1.006	410.095
STANDARD DEVIATION		0.418	0.150	0.537	0.017	431.988	407.461	0.070	53.643

TABLE 13. INTACT BREAST OAR DATA SHEET FOR HYBRID 2 BEAMS

PATIENT ID	FIELD_IS	HEART_D40_IS	HEART_D20_IS	IPSILATERAL LUNG_D45_IS	IPSILATERAL LUNG_D35_IS	WHOLE LUNG_D25_IS	WHOLE LUNG_D20_IS	CONTRA BREAST
001	2-OPTIMISED FIELDS	0.55	1.03	4.28	7.15	4.18	6.50	
002	2-OPTIMISED FIELDS	0.50	1.22	1.12	1.50	1.11	1.43	
003	2-OPTIMISED FIELDS	0.80	1.38	2.57	3.99	2.42	3.58	
004	2-OPTIMISED FIELDS	0.60	1.08	2.11	2.90	1.98	2.63	
005	2-OPTIMISED FIELDS	0.58	1.11	1.84	2.55	1.74	2.34	
006	2-OPTIMISED FIELDS	0.53	1.01	2.26	3.44	1.98	2.84	0.
007	2-OPTIMISED FIELDS	0.87	1.60	4.11	6.70	4.10	6.17	
008	2-OPTIMISED FIELDS	0.35	0.74	1.58	2.26	1.78	2.42	
009	2-OPTIMISED FIELDS	0.75	1.34	1.92	2.49	2.26	2.74	
010	2-OPTIMISED FIELDS	0.51	0.96	2.44	2.94	2.60	3.04	
011	2-OPTIMISED FIELDS	0.55	1.07	2.54	3.36	3.25	4.07	
012	2-OPTIMISED FIELDS	0.59	1.45	1.32	1.66	1.05	1.34	

013	2-OPTIMISED FIELDS	1.21	2.46	2.58	3.73	1.97	2.69	
014	2-OPTIMISED FIELDS	0.92	1.81	1.45	2.06	1.14	1.58	
015	2-OPTIMISED FIELDS	0.93	1.81	1.57	2.07	1.30	1.62	
016	2-OPTIMISED FIELDS	1.88	4.24	1.29	1.61	0.93	1.10	
017	2-OPTIMISED FIELDS	1.17	2.89	2.53	4.56	1.75	2.91	
018	2-OPTIMISED FIELDS	1.20	2.39	1.76	2.30	1.43	1.85	
019	2-OPTIMISED FIELDS	1.90	5.70	2.75	3.95	2.13	2.89	
020	2-OPTIMISED FIELDS	2.47	6.01	3.44	5.54	2.55	3.58	
021	2-OPTIMISED FIELDS	1.76	9.75	3.91	6.67	2.63	4.03	0.
MEAN		0.982	2.431	2.351	3.497	2.108	2.921	0.4
STANDARD DEVIATION		0.561	2.195	0.909	1.691	0.883	1.385	0.2

TABLE 14. INTACT BREAST OAR DATA SHEET FOR HYBRID 5 BEAMS

PATIENT ID	FIELD_IS	HEART_D40_IS	HEART_D20_IS	IPSILATERAL LUNG_D45_IS	IPSILATERAL LUNG_D35_IS	WHOLE LUNG_D25_IS	WHOLE LUNG_D20_IS	CONTRA BREAST
001	5-OPTIMISED FIELDS	2.15	3.86	10.47	14.95	10.30	13.20	
002	5-OPTIMISED FIELDS	2.20	3.24	2.96	3.49	2.93	3.38	
003	5-OPTIMISED FIELDS	2.30	4.09	7.02	9.10	6.87	8.46	
004	5-OPTIMISED FIELDS	2.62	3.70	4.82	6.00	4.68	5.61	
005	5-OPTIMISED FIELDS	1.95	3.51	6.55	7.68	6.44	7.41	
006	5-OPTIMISED FIELDS	1.59	2.31	5.60	7.19	5.14	6.43	0.
007	5-OPTIMISED FIELDS	2.41	6.22	12.19	15.58	12.14	15.00	
008	5-OPTIMISED FIELDS	1.97	3.15	5.47	6.46	5.77	6.63	
009	5-OPTIMISED FIELDS	2.10	3.48	7.24	8.24	7.83	8.70	
010	5-OPTIMISED FIELDS	2.07	2.87	7.94	8.77	8.23	8.98	
011	5-OPTIMISED FIELDS	1.53	2.44	6.82	7.92	7.79	8.82	
012	5-OPTIMISED FIELDS	2.59	4.58	2.72	3.55	3.81	4.44	

013	5-OPTIMISED FIELDS	2.51	4.38	8.37	10.03	6.86	8.61	
014	5-OPTIMISED FIELDS	2.32	3.54	4.15	5.29	3.75	4.46	
015	5-OPTIMISED FIELDS	2.56	4.86	5.48	6.24	5.28	5.86	
016	5-OPTIMISED FIELDS	3.53	6.38	5.27	6.03	3.93	4.58	
017	5-OPTIMISED FIELDS	3.51	7.68	6.55	9.16	6.18	7.70	
018	5-OPTIMISED FIELDS	3.07	5.26	5.65	6.60	5.52	6.25	
019	5-OPTIMISED FIELDS	3.58	6.97	5.76	7.33	4.72	6.01	
020	5-OPTIMISED FIELDS	2.97	7.94	8.63	13.46	6.17	9.01	
021	5-OPTIMISED FIELDS	2.93	10.40	9.42	13.64	6.88	9.65	1.
MEAN		2.498	4.803	6.623	8.415	6.249	7.581	1.1
STANDARD DEVIATION		0.577	2.040	2.270	3.346	2.154	2.753	0.3

TABLE 15. INTACT BREAST OAR DATA SHEET FOR IMRT

PATIENT ID	FIELD_IS	HEART_D40_IS	HEART_D20_IS	IPSILATERAL LUNG_D45_IS	IPSILATERAL LUNG_D35_IS	WHOLE LUNG_D25_IS	WHOLE LUNG_D20_IS	CONTRA BREAST
001	5-OPTIMISED FIELDS	2.49	5.13	11.30	15.47	13.24	16.17	3.
002	5-OPTIMISED FIELDS	2.34	5.59	7.82	9.04	7.74	8.86	3.
003	5-OPTIMISED FIELDS	2.93	9.32	11.56	13.61	11.58	13.27	2.
004	5-OPTIMISED FIELDS	2.47	5.91	10.80	12.51	11.25	12.59	
005	5-OPTIMISED FIELDS	2.41	4.06	8.66	10.04	9.73	11.00	3.
006	5-OPTIMISED FIELDS	1.96	3.00	10.00	12.13	9.99	11.58	4.
007	5-OPTIMISED FIELDS	2.33	5.06	11.96	15.38	12.01	14.79	3.
008	5-OPTIMISED FIELDS	2.14	7.03	10.97	12.89	11.59	13.29	4.
009	5-OPTIMISED FIELDS	2.32	11.83	10.63	11.83	11.34	12.34	1.
010	5-OPTIMISED FIELDS	2.27	3.58	13.21	14.60	13.67	14.91	
011	5-OPTIMISED FIELDS	1.91	3.92	13.29	14.44	14.30	15.25	1.
012	5-OPTIMISED FIELDS	2.61	5.95	4.04	4.90	5.81	6.85	

013	5-OPTIMISED FIELDS	2.84	5.67	12.38	14.67	11.60	13.30	
014	5-OPTIMISED FIELDS	2.96	5.84	10.87	13.15	10.97	12.57	
015	5-OPTIMISED FIELDS	3.31	6.73	10.66	12.29	10.40	11.70	
016	5-OPTIMISED FIELDS	4.13	9.33	10.92	12.39	8.74	9.83	
017	5-OPTIMISED FIELDS	3.84	8.60	10.65	12.90	10.30	11.89	
018	5-OPTIMISED FIELDS	3.31	6.39	10.36	11.47	10.28	11.16	
019	5-OPTIMISED FIELDS	3.58	10.11	11.03	13.42	9.18	11.51	
020	5-OPTIMISED FIELDS	3.75	9.83	10.88	16.10	10.43	12.43	
021	5-OPTIMISED FIELDS	2.61	5.70	12.48	16.49	12.30	14.24	4.
MEAN		2.786	6.599	10.689	12.844	10.783	12.359	3.1
STANDARD DEVIATION		0.626	2.326	1.945	2.551	1.906	2.136	1.1

TABLE 16. INTACT BREAST OAR DATA SHEET FOR VMAT

PATIENT ID	FIELD_IS	HEART_D40_IS	HEART_D20_IS	IPSILATERAL LUNG_D45_IS	IPSILATERAL LUNG_D35_IS	WHOLE LUNG_D25_IS	WHOLE LUNG_D20_IS	CONTRA BREAST
001	2-HALF-ARCS	2.84	6.77	15.45	18.79	15.47	18.27	4.
002	2-HALF-ARCS	4.83	10.93	14.42	16.92	14.28	16.48	4.
003	2-HALF-ARCS	4.08	9.19	17.51	20.23	17.17	19.56	3.
004	2-HALF-ARCS	3.02	6.69	13.53	15.58	13.51	15.18	
005	2-HALF-ARCS	2.49	4.46	11.61	14.34	11.67	13.84	4.
006	2-HALF-ARCS	3.08	5.98	9.96	13.27	10.46	12.78	4.
007	2-HALF-ARCS	3.25	6.99	13.53	18.87	13.48	18.01	4.
008	2-HALF-ARCS	2.59	4.37	10.33	12.61	11.03	13.14	4.
009	2-HALF-ARCS	3.18	5.67	12.88	14.49	13.81	15.28	1.
010	2-HALF-ARCS	3.17	4.83	11.38	13.37	12.00	13.90	
011	2-HALF-ARCS	2.98	6.22	10.92	15.65	11.84	12.58	
012	2-HALF-ARCS	3.47	10.70	11.34	13.77	9.76	11.52	

013	2-HALF-ARCS	4.41	12.82	12.25	16.88	12.00	14.48	
014	2-HALF-ARCS	4.21	10.84	11.28	15.67	11.86	13.26	
015	2-HALF-ARCS	3.85	10.76	11.30	14.53	10.70	12.72	
016	2-HALF-ARCS	4.83	18.05	10.96	14.21	7.35	8.57	
017	2-HALF-ARCS	4.50	14.95	11.37	15.55	10.28	12.75	
018	2-HALF-ARCS	4.25	12.36	11.20	14.01	11.20	12.90	
019	2-HALF-ARCS	4.11	19.52	11.29	15.95	9.00	12.09	
020	2-HALF-ARCS	4.53	17.12	11.75	15.93	9.88	12.42	
021	2-HALF-ARCS	3.57	11.69	14.15	18.06	11.98	14.50	5.
MEAN		3.678	10.043	12.305	15.651	11.844	14.011	4.1
STANDARD DEVIATION		0.720	4.467	1.814	1.989	2.183	2.449	1.1