This work is dedicated to my late grandmother,
Adada
rest in peace

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the target volumes receiving dose between 5 and 25 Gy (average percent volume was 33% for the TomoTherapy plan and 5 % for the electron beam plan). This could affect the radiation oncologist's decision to use TomoTherapy for younger patients who are at greater risk of developing radiation-induced secondary cancers.

Conclusion: The study showed TomoTherapy can deliver dose distributions the radiation oncologist judges to be equal to or better than that of a conventional electron beam PMRT plan for five treatment plans.

Chapter 1
Introduction

1.1. Overview

During the last decade, the radiotherapy clinic has seen numerous advances in technology designed to deliver practical and highly conformal dose distribution that better spare critical organs while dosing planning PTV volumes (PTVs) to tumorcidal levels. Intensity-modulated radiotherapy (IMRT), using multi-leaf collimators and advanced 3D treatment planning systems capable of inverse planning, is the most well known recent advance in radiotherapy technology (Galvin et al. 2001). IMRT with the help of a computerized optimization algorithms provides variable-intensity fields that replace uniform intensity ones. Typically, IMRT improves PTV coverage and conformality and reduces PTV dose inhomogeneity. The principle of IMRT is to treat a patient from a number of different directions (or continuous arcs) with beams of non-uniform fluences, which have been optimized to deliver a high dose to the PTV volume and acceptable low dose to the surrounding normal structures (Khan 2003).

Tomotherapy is a novel approach to the delivery of IMRT (Mackie et al. 1993). Figure 1 shows TomoTherapy Hi-Art System developed by the TomoTherapy Inc. (Madison, WI) was designed to provide tomotherapy in a helical motion much like current CT machines acquire images. TomoTherapy delivers photon IMRT dose distributions with a continuously rotating, helical fan beam using a binary multi-leaf collimator, and it utilizes an onboard mega-voltage computerized tomography system (MVCT) that allows for image-guided radiotherapy (IGRT). As in an ordinary helical computed tomography (CT) scanner, the patient is continuously translated through a ring gantry as the fan beam rotates.

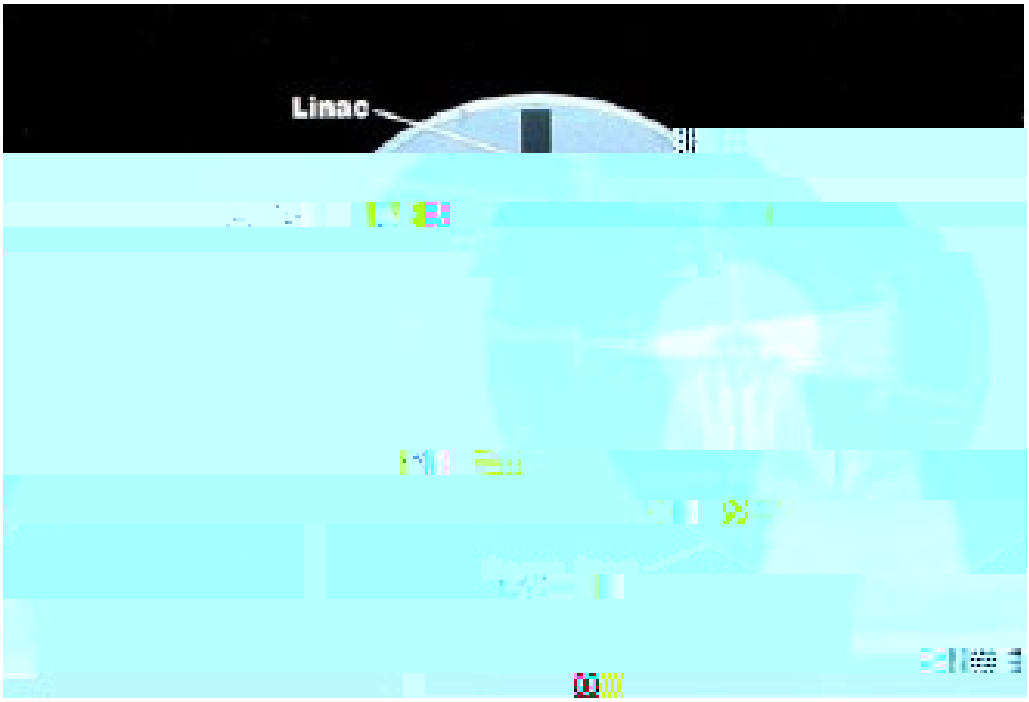


Figure 1. Schematic of helical TomoTherapy unit. The commercially available TomoTherapy system does not have an on-board kilo voltage imaging system, rather it uses a megavoltage CT (Courtesy TomoTherapy Inc. Madison, WI)

TomoTherapy differs from fixed-beam linear accelerator IMRT in several ways. First, in fixed-beam IMRT beam directions are selected by the planner before the beam intensity patterns are modulated with the optimizer. TomoTherapy uses all beamlet orientations within a 40-cm wide fan beam that intersect the PTVs and optimally weights them to achieve user-defined volumetric dose goals and limitations. A beamlet is a single leaf-pair opening in one projected angle. There are 64 binary leaf-pairs in any projected angle and 51 projected angles in each rotation, making a total of 3264 possible beamlets in each rotation. This greater degree of freedom on the part of the optimizer in selecting beam incidence may allow for improvements in the planning of more complex treatments. However, it also may irradiate significant regions of tissue outside the PTV to achieve volumetric dose goals unless dose constraints have been placed on those regions. Also, the TomoTherapy helical delivery allows the treatment of extended treatment

volumes without the need for junctioning fields (Bauman et al. 2005). However, TomoTherapy beams are limited to axial beams, i.e., beams directed perpendicular to the TomoTherapy gantry axis.

One obvious difference between a multi-modality linear accelerator and TomoTherapy is that the latter does not offer electron beams. Electron beams are advantageous in that dose falls rapidly off distal to the treatment volume which makes this modality ideal for treating superficial PTVs, often with a single beam. There are a multitude of treatment sites that use electrons exclusively or in combination with photon beams, especially sites within the breast and head and neck (Tapley 1976 and Hogstrom 2003a).

1.2. Significance of TomoTherapy vs. Electron Beams

Published comparisons between TomoTherapy and mixed beams are limited in number. Lock et al. (2002) compared a conventional photon/electron total scalp irradiation technique Tung et al. (1993) with a serial tomotherapy treatment delivered with the NOMOS MIMiC system. They concluded that the conventional technique was superior in sparing critical structures, such as the eyes, although the tomotherapy treatment delivered much greater dose homogeneity to the PTV and provided better sparing of the parotid glands. However, the study did not explore the possibility of relaxing PTV dose homogeneity to better spare critical structures and achieve a comparably similar plan to the conventional irradiation technique. Orton et al. (2005) showed that a TomoTherapy dose distribution was superior for treating total scalp due to

dose on the surface while sparing critical structures due to limited particle range making electrons a good candidate to treat superficial PTVs. However for large treatment areas, abutting adjacent electron fields can in some circumstances result in either overdosing or under dosing the junctioned areas. In Mary Bird Perkins Cancer Center (MBPCC) where the project was conducted, shifting the abutment borders during the course of treatment is done to minimize dose heterogeneity at field junctions. This requires considerable effort in the planning of both field shapes and positions, and requires careful observation of the abutment regions during the course of radiotherapy.

Eliminating problems associated with a field junction is often necessary, especially for large, superficial chest wall PTVs in post-mastectomy radiation therapy (PMRT). An ideal technique should deliver a homogenous dose to the PTV including the matchline, if deemed to be a risk, while minimizing normal tissue radiation exposure without compromising the PTV treatment. Although this can be achieved in part with arc therapy (Hogstrom 2003a), that technology is complex and not often used.

Prior studies by Krueger et al. (2003) demonstrated the feasibility and possible utility of IMRT for post-mastectomy breast patients. Unlike traditional methods, the IMRT technique significantly reduced problems associated with field junctioning and improved the dose homogeneity in the chest wall. The natural extension of this technique for PMRT is the use of arcing modulated photon beams, and TomoTherapy may seem an ideal candidate for this technique. The ability to treat extended treatment volumes without the need for fixed-beam field junctioning, and the greater degree of freedom on part of the optimizer in selecting beam incidence, may give TomoTherapy an advantage over conventional fixed-beam linear accelerator techniques.

Although TomoTherapy is a relatively new technology, its presence is being felt throughout the radiotherapy community. When using a new technology, the question of improvement in dose delivery, cost, and outcome create a complex environment to answer the question: Does the technology significantly improve patient care (Lock et al. 2002)? This investigation focused on a more specific question: Are TomoTherapy treatment plans for PMRT patients comparable to conventional (electron field) technique treatment plans?

1.3. Postmastectomy Radiation Therapy (PMRT)

1.3.1. Overview

Although radiotherapy in the treatment of breast cancer is associated with an ncreased risk of complication, subsequent studies showed its advantage in improving cancer survival overrides the risks associated with the radiation treatment. Rutqvitst et al. (1990) showed that post-operative radiation therapy for early breast cancer produces a sustained improvement of recurrence free survival, mainly through prevention of locoregional recurrences. Other studies have subsequently shown a significant improvement in survival for patients who underwent radiation treatment after surgical mastectomy (Ragaz et al. 1997, Overgaard et al. 1997 and 1999). On the basis of these and other studies, a National Institutes of Health consensus panel recommended locoregional PMRT in patients with $\geq$ 4 positive axillary lymph nodes and/or T3 and T4 staged lesions (Eifel et al. 2000). As a result, many institutions offer comprehensive PMRT for high risk breast cancer patients who have undergone mastectomy.

PMRT PTVs the chest wall (CW) and regional lymph nodes such as the supraclavicular (SCl), the internal mammary chain (IMN), and the axillary (AX) nodes.

technique being accepted as a gold standard. Pierce et al. (2002) investigated seven commonly used conventional techniques for irradiation of post mastectomy CW patients, namely: 1. Standard tangents; 2. Electron fields; 3. Cobalt fields; 4. Reverse hockey stick (RHS); 5. 30%/70% Photon/Electron mix; 6. 20%/80% Photon/Electron mix; and 7. Partially wide tangent fields (PWTF). The study concluded that none of the techniques combined the best CW and IMN coverage with minimal lung and heart complication probabilities, i.e., no single technique was found to be superior for all treatment goals. However, among the seven discussed techniques, the use of PWTFs was found to produce the most appropriate compromise of PTV coverage and normal tissue sparing. The study did not take IMRT into consideration. In conclusion, the selection of PMRT technique should be based on clinical discretion and technical expertise available to implement complex treatment plans. Clinical discretion encompasses estimated risk reduction in locoregional recurrence and its potential impact on survival, and the predicted complication risk for each patient.

1.3.2. Conventional Electron PMRT Technique

In our study, we have chosen to compare TomoTherapy with a conventional electron and photon beam technique commonly used to treat PMRT patients at Mary Bird Perkins Cancer Center. In this technique, a total of five fields are typically used (Figure 2). The medial CW is treated with an anterior electron field and the lateral CW is treated with an oblique electron field. The IMN is treated with an anterior electron field, and parallel-opposed photon fields (6 MV) are used to treat the region containing the supraclavicular/axillary nodes (SCl/AX). As discussed in the previous section, matching adjacent electron fields presents a considerable problem for this technique at the border of medial and lateral chest-wall fields because converging central axes create a large

overlap (Hogstrom 2003a). This problem is addressed in the clinic by moving the junction between the lateral and medial fields every week over the typical 5-week course of treatment to reduce the magnitude of dose heterogeneity.

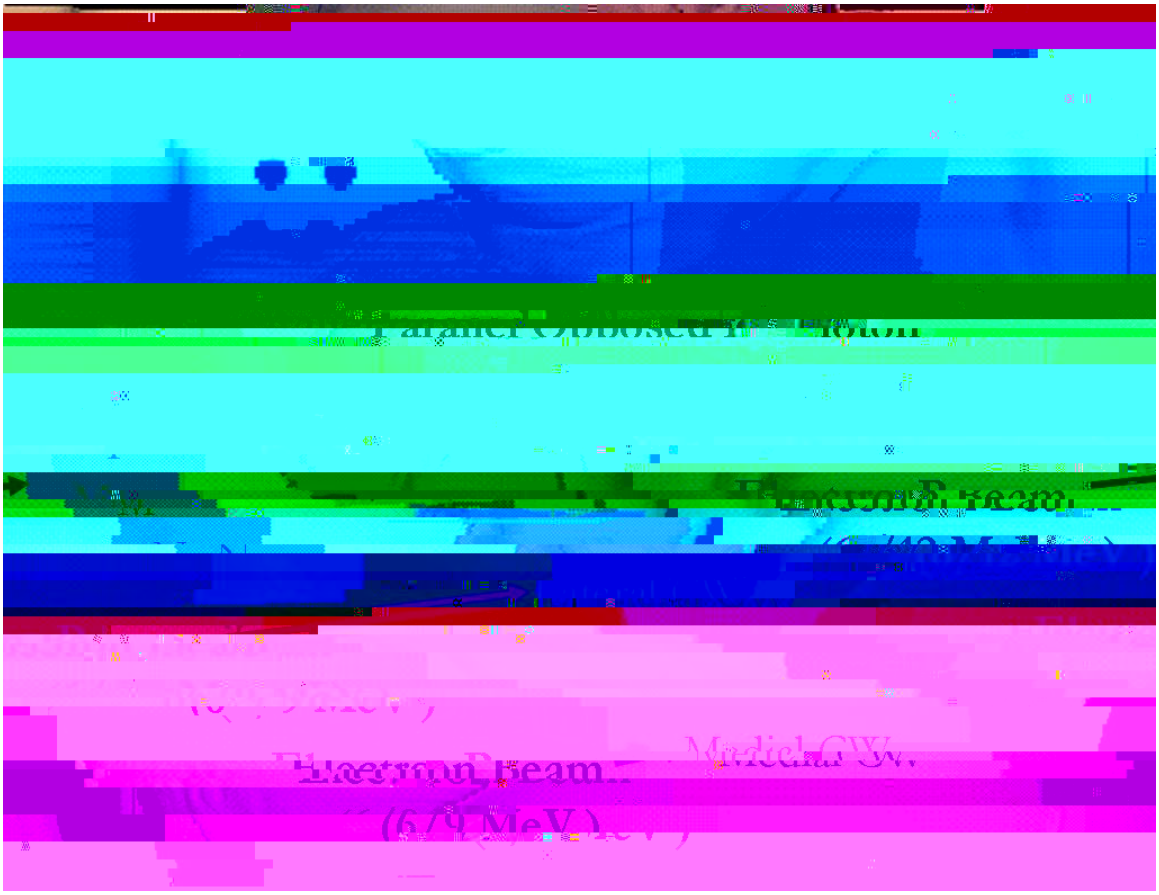


Figure 2. Conventional electron PMRT technique. The CW and IMN are treated with electron beams and the SCl/AX is treated with photon beams.

1.3.3. Complications Associated with PMRT

The close proximity of the lung and heart to the CW and IMN poses probleN po-12(e)4(bX09.2 Tm [(45

if patients are likely to receive systemic chemotherapy agents with known cardiac and pulmonary toxicity (Krueger et al. 2003). Hence, individual treatment planning warr

their study indicated that the radiation treatment of women with breast cancer does not significantly increase the risk of development of contralateral breast cancer. They attributed the negative finding to the age at radiation exposure. Most published positive findings for radiation-associated risk has been concentrated in young patients, less than 30 years at time of exposure (Hancock et al. 1993).

1.3.4. IMRT

One approach that may solve the problem of normal tissue complications is intensity-

1.4. Hypothesis/Specific Aims

The hypothesis of current study is that TomoTherapy can plan dose distributions for

the TomoTherapy and the conventional treatment plans. Along with the plans, provide multiple choice questionnaires to the radiation oncologist for this evaluation.

Aim 5: Determine biological treatment plan metrics. Calculate and compare the tumor control probability (TCP), the normal tissue complication probability (NTCP), and the secondary cancer complication probability (SCCP) for both techniques. The purpose of these data is to supplement the comparisons of two rival plans (conventional and the TomoTherapy plans) with radiobiological modeling of the impact of the treatment.

Chapter 2
Materials and Methods

The third goal was to generate and compare dose-volume metrics from both the TomoTherapy and the conventional electron beam treatment plans.

The fourth goal was to have a radiation oncologist evaluate both plans for clinical acceptability, i.e., is the plan acceptable for treating the patient? The radiation oncologist also was to review both plans side-by-side and determine which plan was better (or if they were similar). A questionnaire was generated to help the radiation oncologist in the decision process.

The fifth goal was to generate and compare the radiobiological impact of the PMRT plans using standard radio-biological models. Radiobiological metrics of interest in this study included:

1. PTV tumor control probability (TCP).

scan data could not be directly exported from a Pinnacle workstation to the TomoTherapy planning system.

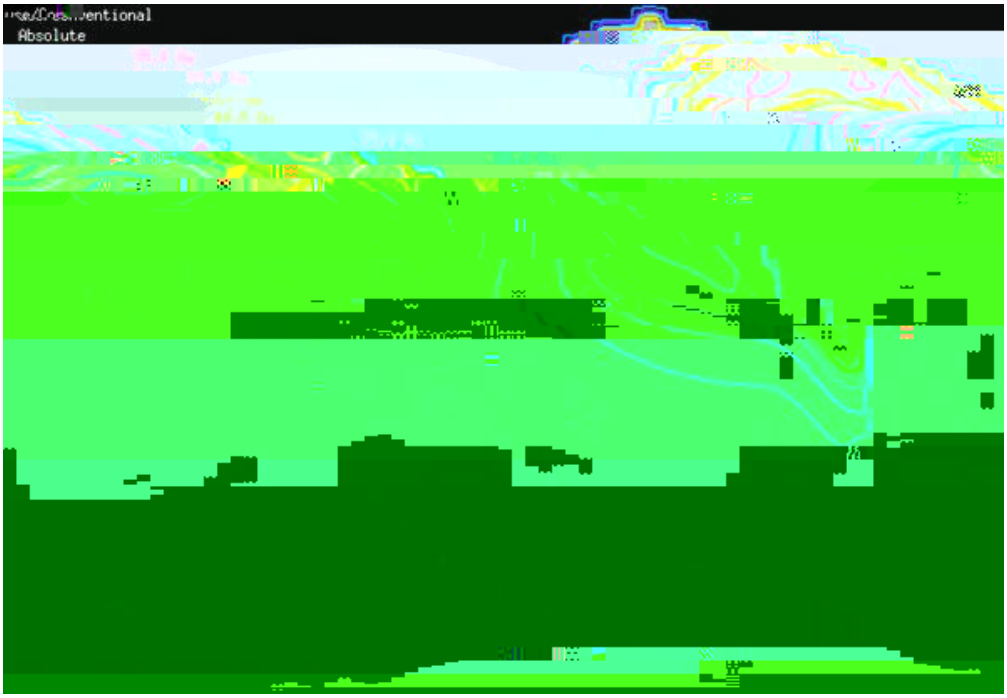
The Pinnacle treatment plan was retrieved and imported into the Pinnacle workstation. The patient name and medical record number were stripped from the treatment plan and replaced with a code number. The code number was linked to the patient name and medical record number on a master list kept independently by the project director. This was done to maintain patient confidentiality in accordance with a protocol approved by an institutional review board.

PTVs were generated for each of the PMRT treatment plans in the patient database, as (1) PTVs are typically not contoured for conventional electron beam PMRT planning, and (2), the TomoTherapy treatment planning system (TPS) is strictly an inverse planning system and requires contoured PTVs and OARs.

All OARs were generated except for the spinal cord which was previously contoured in some patients. Both the lungs were contoured separately using Pinnacle's auto contour tool which uses CT thresholds and appropriate edits was made. The heart chambers (left and right atria and left and right ventricles) were contoured starting at the superior extent of the heart chamber and ending at the apex. The contralateral breast was outlined starting at the clavicular head and ending at the inframammary fold. Also, the spinal cord and the 0.5 cm expanded spinal cord were outlined. A structure compromising all normal tissue, excluding specified OARs and PTVs, was auto-contoured. This was defined by subtracting the volumes of PTVs and specified normal tissues from the whole patient volume. The entire contour set was reviewed by a certified dosimetrist and later by the radiation oncologist upon reviewing the dose distributions.

Since the prescribed dose for the chest wall (CW) can differ from prescribed dose for the supraclavicular and axillary (SCl/AX) nodes, separate PTVs are required for TomoTherapy treatment planning. Therefore, two PTVs were generated, one for the CW and the IMN, and a second for the supraclavicular/axillary nodes (SCl/AX). The IMN was considered part of the CW PTV because the dose prescriptions for each were the same in each of the patient cases.

The PTVs were generated from the conventional Pinnacle treatment plans by converting an isodose line to a contour. The isodose line chosen for generating a PTV was 90% of the prescribed dose. The prescribed dose in each case was the maximum dose delivered to water along the central axis. In order to separate the two PTVs, the prescription for SCl/AX was set to zero when contouring CW and vice versa. Pinnacle allows turning individual prescription assigned to filed(s) on/off, when a multiple prescriptions present in a treatment plan. As a result, the dose distribution from individual fields can easily be seen. If the automatically-generated PTV was found broken up into several contours on the same slice resulting in “contour islands,” the PTV contours were

a) 

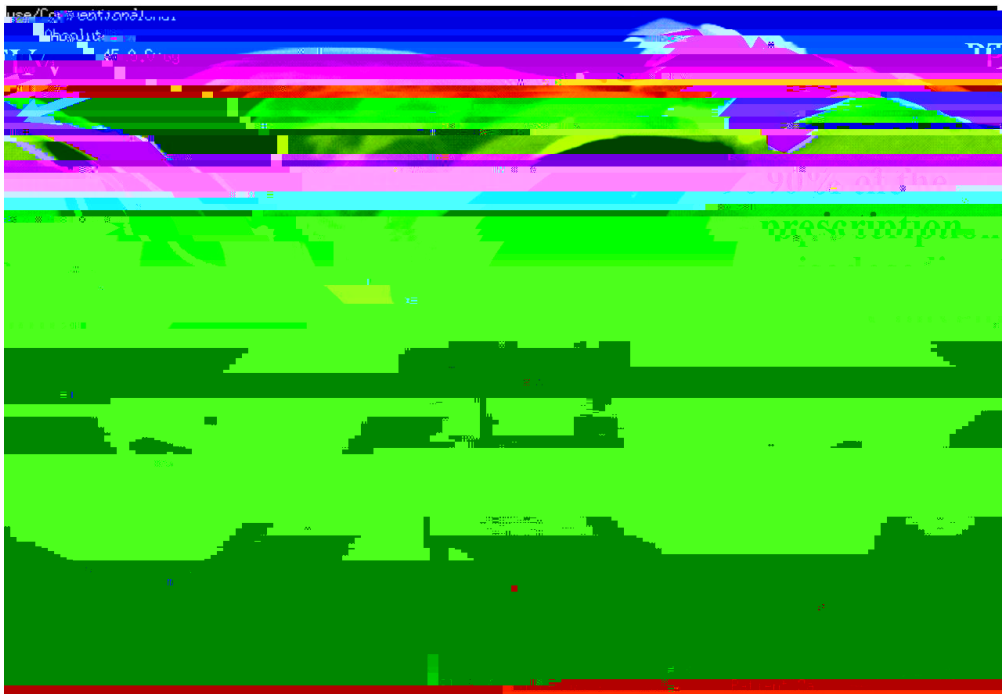
b) 

Figure 3 shows an example of converting the 90% isodose line (45 Gy) shown in (a) to a CW PTV (b).The 45 Gy isodose line, 90% of the prescribed dose, is shown as a thick yellow contour. The converted PTV is shown as a solid red area

2.3. Aim 2: TomoTherapy PMRT Treatment Plans

2.3.1. Importing CT Data

The TomoTherapy treatment planning system was used to generate an inverse IMRT plan for 5 patients. CT scan data was imported into the TomoTherapy treatment planning 20workstation from the CT workstation (GE Discovery ST, Model #: 316097CN5) after being retrieved from long term storage. Patient name and medical record number were removed and changed to a code before sending CT images to the TomoTherapy planning system. CT image slices, which were 5-cm or more beyond the superior and inferior extent of the PTVs and did not include OARs, were removed from the CT scan data to

2.3.3. TomoTherapy Plan Parameters

1. A temporary ROI was generated by expanding the PTV by 1 cm in all directions.

2. Another temporary ROI was generated by expanding the PTV by 1.5 cm in all directions.

3. The final “ring” ROI was generated by subtracting the first ROI from the second.

The ring dose limiting structures were labeled as region at risk (RAR) for TomoTherapy treatment planning.

Other dose limiting structures were utilized in the TomoTherapy treatment plan as needed. A dose limiting structure which acts as a buffer zone was drawn approximately one cm superiorly and inferiorly from the PTVs to limit patient dose outside the PTVs. A directional blocking RAR was utilized to prevent beamlets from coming in the direction where patient anatomy was outside the CT scan field of view (FOV) Figure 5.

2.3.5. TomoTherapy Optimization and Dose Calculation

Once all such constraints were defined, optimization and dose calculation commenced. Table 2 lists typical PTV and RAR constraints upon completion of optimization. Dose constraints such as importance levels and maximum/minimum penalties were specified to all structures (PTVs and RARs). Compared to distal critical structures, a large value was used for the importance and max dose penalty for adjacent ones. In general, OARs dose limits were made as low as possible without degrading dose delivered to the PTV or creating unnecessary dose to large volumes of normal tissue. Also dose to normal tissue peripheral to PTVs was minimized without degrading PTV dose homogeneity or OAR dose sparing.

Table 2. Typical PTV (a) and RAR (b) constraints upon completion of optimization.

(a)

Name	Importance	Max Dose (Gy)	Max Dose Penalty	DVH Vol (%)	DVH Dose (Gy)	Min Dose (Gy)	Min Dose Penalty
CW	100	53	100	50	50	50	250
SC/AX	1200	55	1000	50	50	48	5

(b)

Name	Importance	Max Dose (Gy)	Max Dose Penalty	DVH Vol (%)	DVH Dose (Gy)	DVH Penalty

Fractionation is dividing up the patient's dose prescription into a number of different sessions, all of which add up to the total prescribed dose. The temporary dose distribution file (EOPDose.img) was saved along with the header file into a separate directory on the TomoTherapy workstation and was exported to a separate Pinnacle plan trial in the patient database.

2.4. Aim 3: Generate Dose-Volume Treatment Plan Metrics

Dose-volume treatment plan metrics were generated using (1) ADAC Pinnacle, (2) Matlab version 7.1 (MathWorks, Inc., Natick, Massachusetts), and (3) Microsoft office excel 2003 (Microsoft, Inc., Redmond, Washington). The Pinnacle treatment plan trial dose-volume information was exported to the in-house program as an RTOG file. Differential dose-volume histograms (dDVHs) embedded in the RTOG file were read in by the in-house program to generate relevant dose-volume metrics. The dose-volume metrics of interest in this study included:

1. DVHs for each PTV and OAR.
2. Mean and standard deviation of dose to each PTV.
3. Difference in PTV dose between 10% and 90% of PTV ($D_{90\%}$-$D_{10\%}$).
4. Volume of lung receiving at least 20 Gy or more.
5. Volume of heart receiving at least 30 Gy or more.
6. Volume of heart receiving at least 15 Gy or more.
7. Volume of contralateral breast receiving at least 5 Gy or more.
8. Mean dose to the contralateral breast.

Both the standard deviation of the PTV and the $D_{90\%-10\%}$, the differencehe%.P-2(or(9)-22.3882d00)

statistically significant relative to the development of pneumonitis. Hence, the volume of lung receiving at least 20 Gy or more was useful in comparing competing treatment plans to evaluate the risk of pneumonitis (Graham et al., 1999). Studies conducted by Gagliardi et al. (1996) showed that the probability of excess cardiac mortality due to IHD is less than 4.5% for the whole heart volume receiving less than 30 Gy. Hence, the percentage of heart that received 30 Gy or less ($V30_{heart}$) was chosen to compare competing treatment plans.

Table 3 lists the dose/volume limits specific to our clinic. Published tolerance doses and irradiated volumes (Emami, et al. 1991) are generally higher those listed on Table 3. Radiation oncologists at our institution have stricter dose limits than published tolerance doses, which they feel take into account the patient's prior experience, such as chemotherapy. The radiation oncologist specifications were taken into consideration during optimizing the TomoTherapy treatment plans. Also, the volume of the contralateral breast that received 5 Gy or more ($V5_{contralateral\ breast}$), the volume of the heart that received 15 Gy or more ($V15_{heart}$), and the volume of the lung that received 20 Gy or more ($V20_{lung}$) were noted when generating the dose-volume treatment plan metrics.

Table 3. Radiation oncologist specifications

Organ	Dose Limit	Volume
Lung	20 Gy	$\leq$ 15%
Heart	15 Gy	$\leq$ 10%
Spinal Cord	10 Gy	$\leq$ 10%
Contralateral Breast	Max 5 Gy	

2.5. Aim 4: Radiation Oncologist Evaluation of Treatment Plans

In the fourth aim, a radiation oncologist evaluated and compared both conventional and TomoTherapy plans. The radiation oncologist was presented with a

are not available in literature, chest wall was considered as a breast to retrieve α and β values and as a skin to retrieve the T_r value. Definitions of α, β and T_r parameters are listed on the following page. The overall probability of tumor control is the product of probabilities of tumor control in each tumor dose bin *i* of the differential dose-volume histogram:

$$TCP = \prod_i TCP_i . \qquad (1)$$

The rest of the parameters in Equations 4, 5, and 6 defined as:

α = cell radio sensitivity (Gy^{-1}).

β = the effectiveness/lethality of radiation (Gy^{-2}).

d_i = D_i/number of fraction (Gy/fraction).

T = treatment time per fraction (hr).

T_r

D_{eff} is biological mean dose called effective dose (Warkentin et al. 2004). The other parameters in Equations 7, 8, and 9 are defined as:

n = a fitting parameter that accounts for the dose-volume dependence of tissue

v_i = is volume ratio (volume that receives D_i / total volume of the structure)

m = a fitting parameter that control the slope of the dose repose curve

D_{50} = the dose at which there is a 50% chance of complication (Gy) within 5yrs

i =the number of individual bins in the differential DVH data.

Radiation pneumonitis was used as an end point for the current study. The parameters used to calculate NTCP are listed on Table 5.

Table 5. Parameters selected to calculate NTCP for lung.

Name	**Value**	**Source**
N	0.87	[Pierce et al. 2002]
M	0.18	[Pierce et al. 2002]
D_{50}	24.5 Gy	[Emani et al. 1991]

2.6.3. Normal Tissue Complication Probability (NTCP) for The Heart

The heart has a low dose-volume complication response, but can be damaged with high dose in small volumes. Therefore, it is appropriate to model it as a serial structure like the spinal cord. The relative seriality model, developed by Kallman et al. (1992), was used to calculate NTCP for the whole heart structure. Cardiac mortality due ischaemic heart disease (IHD) was used as an end point for the current study. NTCP using the relative seriality model is calculated as:

$$NTCP = \{1 - \prod_{i=1}^{n} (1 - P(D_i)^s)^{v_i}\}^{\frac{1}{s}}, \qquad (10)$$

where ( ) 2 $^{\exp(\quad (1 \frac{}{D_{50}}))}$

where: P (D) = the NTCP of the organ irradiated homogenously to dose D_i

v_i = is volume ratio (volume that receives D_i / total volume of the structure)

m = a fitting parameter that control the slope of the dose repose curve

D_{50} = the dose at which there is a 50% chance of complication (Gy)

s = seriality of subunits (ratio of number of serial subunits to all subunits)

γ = The maximum relative slope of the dose response curve

i = the number of individual bins in the differential DVH

The parameters used to calculate NTCP are listed on Table 6.

Table 6. Parameters selected to calculate NTCP for heart.

Name	**Value**	**Source**
D_{50}	52.3 Gy	[Gagliardi et al. 1996]
S	1.0	[Gagliardi et al. 1996]
γ	1.28	[Gagliardi et al. 1996]

2.6.4. Secondary Cancer Complication Probability (SCCP) for The Lung.

The probability of secondary cancer induction was calculated for lung, contralateral breast, and normal tissue using the Schneider model [Schneider et al. 2005a and 2005b]:

$$SCCP_{org} = In_{org} * OED_{org} \ , \qquad (12)$$

Where OED_{org} is the organ equivalent dose calculated as

$$OED_{org} = \frac{1}{N} \sum_{i=1}^{N} D_i e^{-\alpha D_i}$$

The parameters of Equations 12 and 13 are listed below:

α = Cellular radio sensitivity (Gy $^{-1}$).

In_{org} = Absolute cancer incidence provided by the International Commission on Radiological Protection (ICRP 60) and the United Nation Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

N= is dose calculation point

i = the number of individual bins in the differential DVH.

D = dose (Gy).

The parameter values used to calculate SCCP for lung are listed in Table 7. The In_{org} for lung (data is from UNSCEAR) is for the total lung (ipsilateral and contralateral lung). Hence, the individual ipsilateral and contralateral lungs' SCCP values were corrected by multiplying the calculated SCCP values with the respective volume ratio. The residual life expectancy that was used to find the life time SCCP for lung was taken as the difference between the female life expectancy (79.8 yrs) Arias et al.,(2003) and the onset

pm I1

Table 7. Parameters selected to calculate SCCP for lung.

Name	Value	Source
α	$0.129 Gy^{-1}$	[Schneider et al. 2005a]
In_{org}	$8.27/(10^4$. patients. yr. Gy)	[Schneider et al. 2005a]

Table 8. Parameters selected to calculate SCCP for the contralateral breast.

Name	Value	Source
α	$0.085\ Gy^{-1}$	[Schneider et al. 2005b]
In_{org}	$0.78\ (\%\ Gy^{-1})$	[Schneider et al. 2005b]

Table 9. Parameters selected to calculate SCCP for the normal tissue.

Name	Value	Source
α	$0.085\ Gy^{-1}$	[Schneider et al. 2005b]
In_{org}	$1.76\ (\%\ Gy^{-1})$	[Schneider et al. 2005b]

Figure 6 shows a plot of cancer incidence per 10^4 patients per year for solid tumor (i.e., an abnormal mass tissue that usually does not contain cysts or liquid areas) induction as a function of dose. Note that the probability is maximum around 11 Gy and decreases for higher dose values because sterilization of already mutated cells becomes more important. According to the Schneider's model, certain tissue receiving dose between 5 and 25 Gy will have a high probability of solid tumors induction (≥ 0.75) with a mean follow up time of 9.5yrs. Therefore, the volume of normal tissue receiving doses between 5 and 25 Gy was also determined for plan evaluation

Chapter 3
Results

3.1. Format for Presenting Results of Each Patient

The format for presenting the results is the same for all patients. For each patient, the results are presented in the following order:

1. isodose comparison,
2. DVH comparison,
3. radiation oncologist's review of the conventional and TomoTherapy plans, and their comparison,
4. mean and standard deviation of dose to the chest

patients and 43.2 Gy dose line is added for the fourth patient. The color scheme for the isodose lines is consistent for all patients. It should be noted that the TomoTherapy TPS calculates dose in air outside the patient while ADAC Pinnacle TPS sets this dose to zero. This results in isodose lines appearing outside the patient in the TomoTherapy plan.

A cumulative DVH comparison between the conventional and TomoTherapy plans is

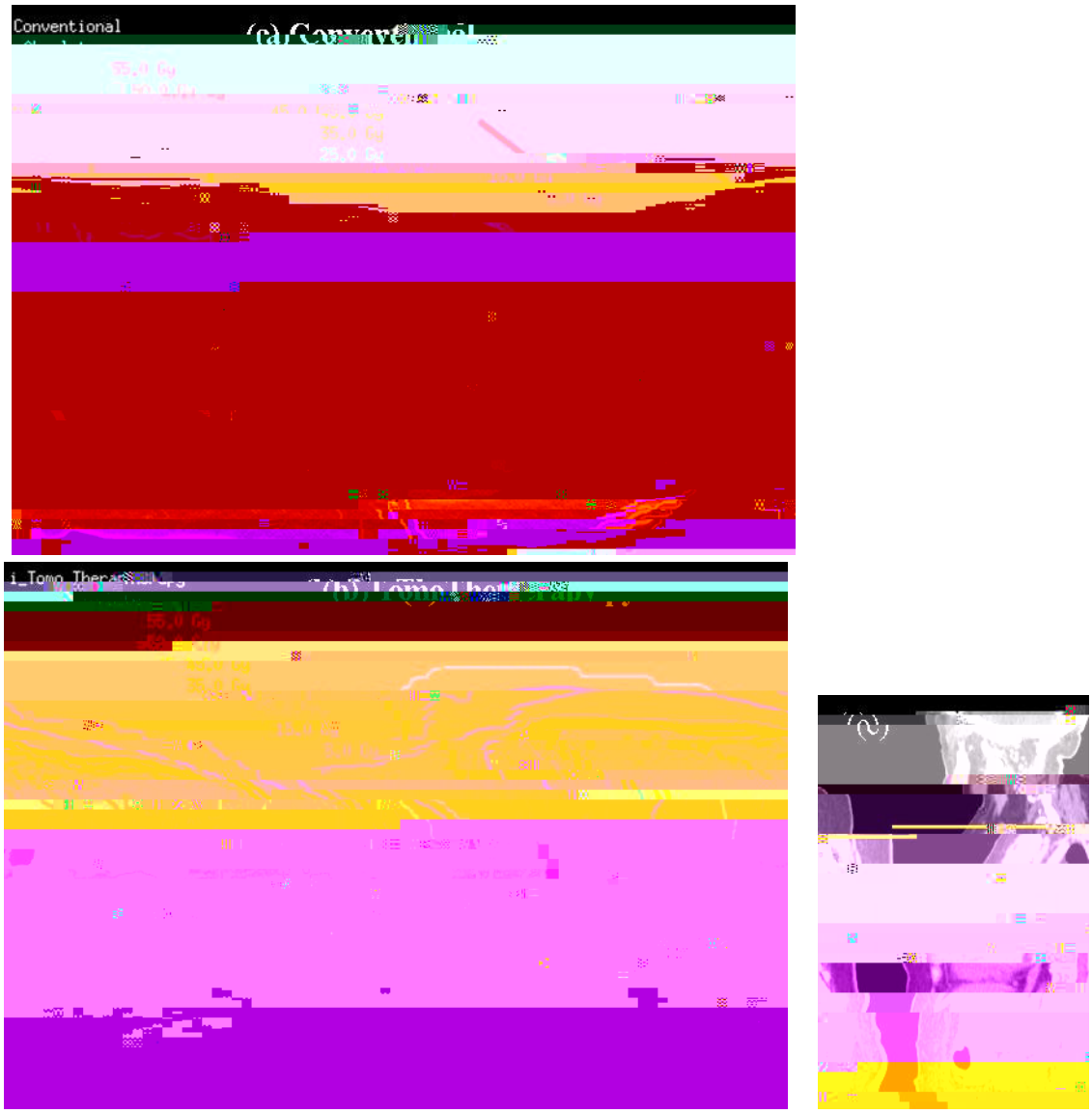


Figure 7. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the supraclavicular nodal region shown on sagittal view (c).

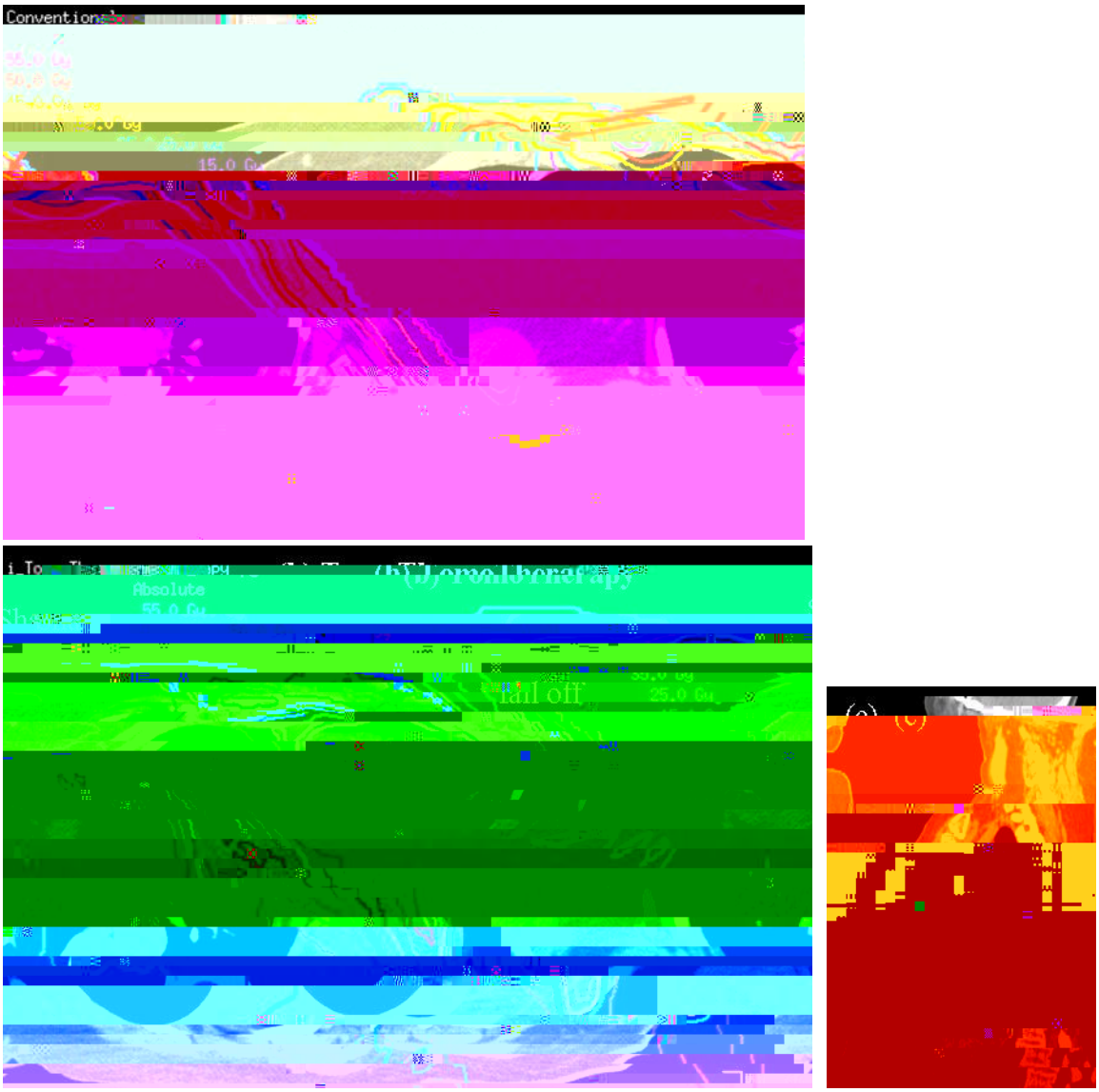
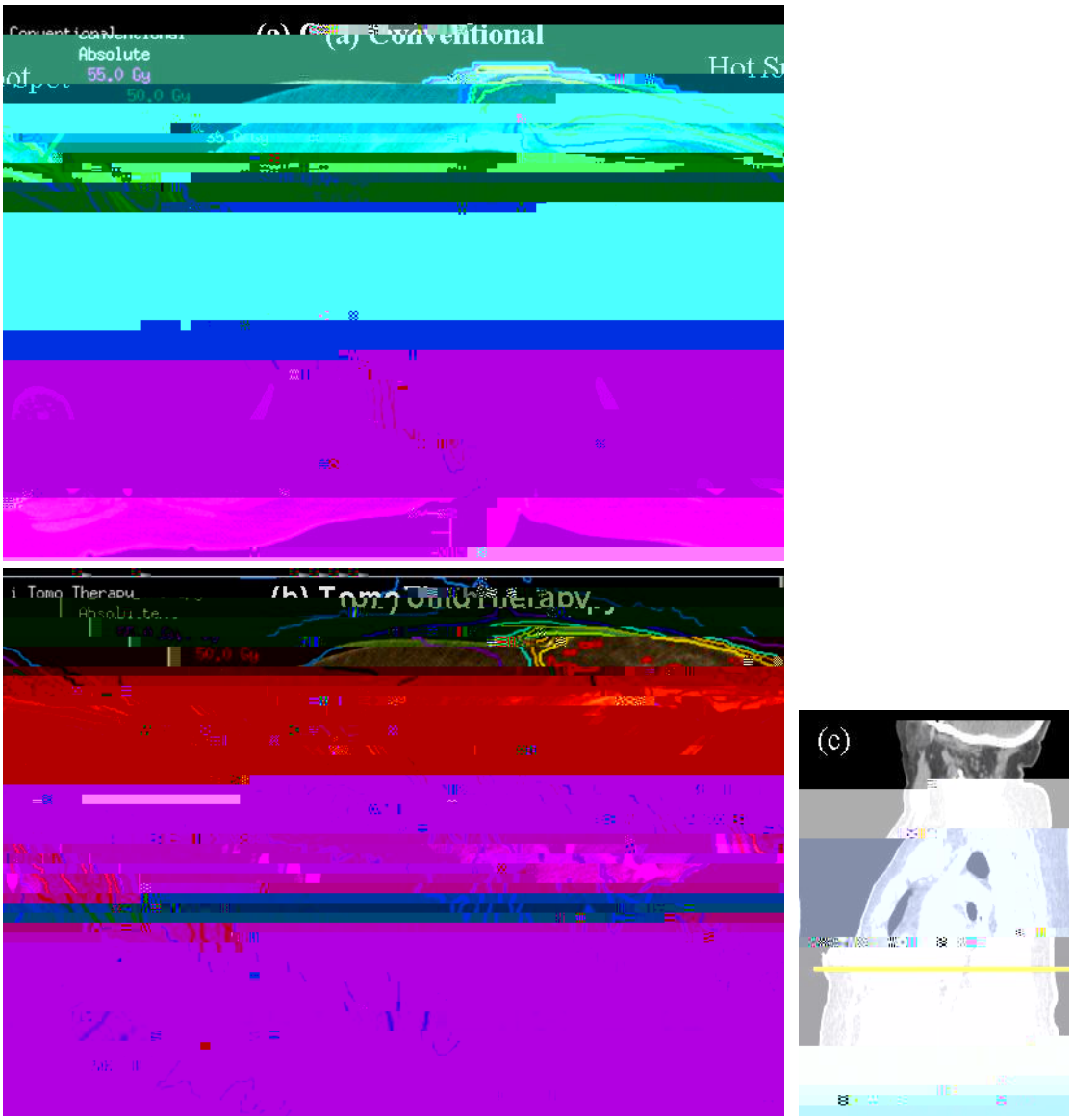


Figure 8. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the IMN region as shown on the sagittal view (c).

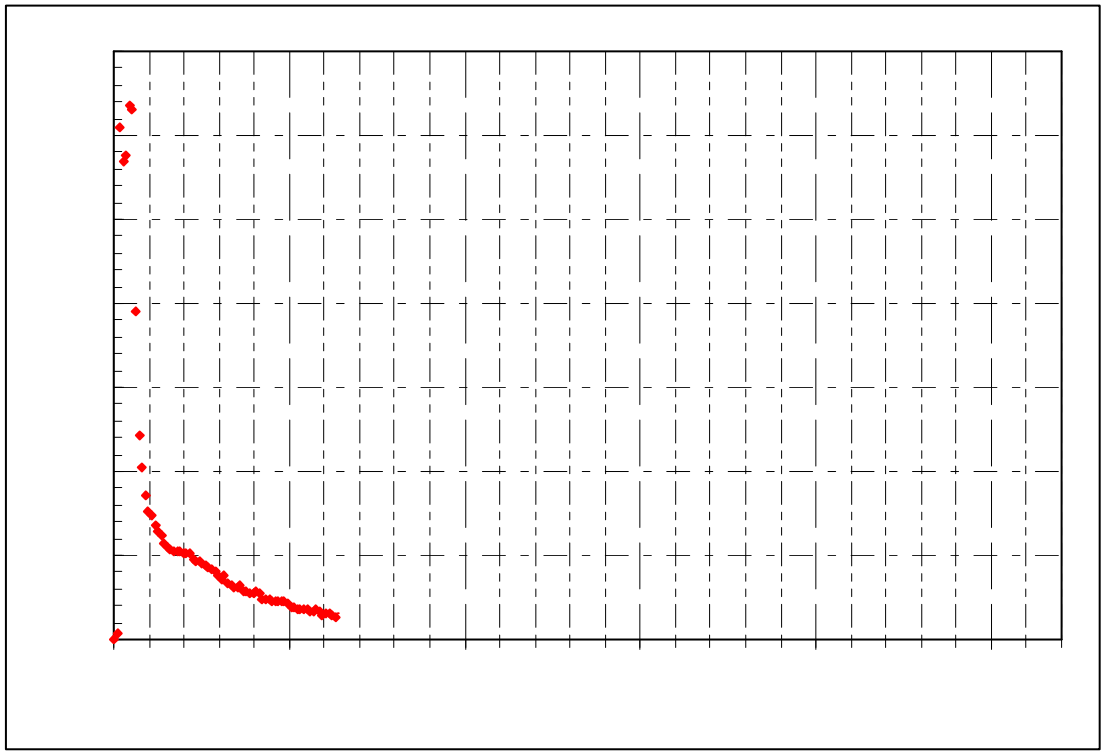
Figure 9 shows the isodose comparison between the conventional plan (Figure 9a) and the TomoTherapy plan (Figure 9b) on a transverse CT image slice near the inferior border of the CW PTV, and is delineated by the yellow line in sagittal midline CT image


(a) Conventional
Absolute
55.0 Gy
50.0 Gy
(c)

the dose to the heart was higher in the TomoTherapy plan and may be of concern if the

3.2.5. Ipsilateral Lung

During optimization of the TomoTherapy plan, a high penalty factor was assigned to the ipsilateral lung objective to force photon beams to come in an oblique direction. As a result, TomoTherapy avoided irradiating it with high doses (20Gy). The ipsilateral lung



relatively higher for the TomoTherapy plan (conventional plan = 0.0001 and TomoTherapy plan = 0.0178).

3.2.8. Normal Tissue

The normal tissue volume receiving between 5 and 25 Gy for this patient was 17.6 cm^3 for the conventional plan and 111.7 cm^3 for the TomoTherapy plan. The calculated SCCP value relatively higher on the TomoTherapy plan (conventional plan =0.003 and TomoTherapy plan = 0.012).

3.3. Patient Two

A 53 – year old female was diagnosed to have an infiltrating ductal carcinoma of the upper outer quadrant of the left breast, stage T3pN2aM0 carcinoma with 4 out of 12 lymph nodes positive with extra-nodal extension. The conventional electron beam PMRT plan had the following fields:

1. AP/PA 6 MV photon beam SCl/AX fields,
2. 12 MeV electron beam IMN field,
3. 6 MeV electron beam medial CW field, and
4. 9 MeV electron beam lateral CW field.

Both the SCl/AX and CW PTVs were irradiated to 50 Gy in 25 fractions.

3.3.1. Isodose Comparison

Figure 12 shows the isodose comparison between the conventional plan (Figure 12a) and the TomoTherapy plan (Figure 12b) on the transverse CT image slice in the region of the supraclavicular nodes delineated by the yellow line in sagittal midline CT image shown in Figure 12c. The yellow 45 Gy isodose line represents the 90% isodose line where the TomoTherapy plan was optimized to match the conventional plan. The conventional plan showed a hot spot of 55 Gy (110% of the prescription dose) in the

medial, anterior portion of the dose distribution, whereas the TomoTherapy plan showed no similar hot spot in that region.

The conventional plan showed a sharper dose falloff than the TomoTherapy plan along the beam edges of the parallel-opposed photon beams of the conventional plan. Greater dose restriction outside the supraclavicular PTV in the TomoTherapy plan during optimization might have resulted in a sharper dose falloff along the “beam edges” delineated by the conventional plan. The TomoTherapy plan also showed a significant volume of tissue outside the PTV receiving low dose (5 Gy or more).However, the TomoTherapy plan showed a greater dose gradient beyond the 45 Gy isodose line in the

However, the TomoTherapy plan showed slightly greater dose gradient beyond the 45 Gy isodose line in the AP direction. This resulted in lower volume of dose to ipsilateral lung.

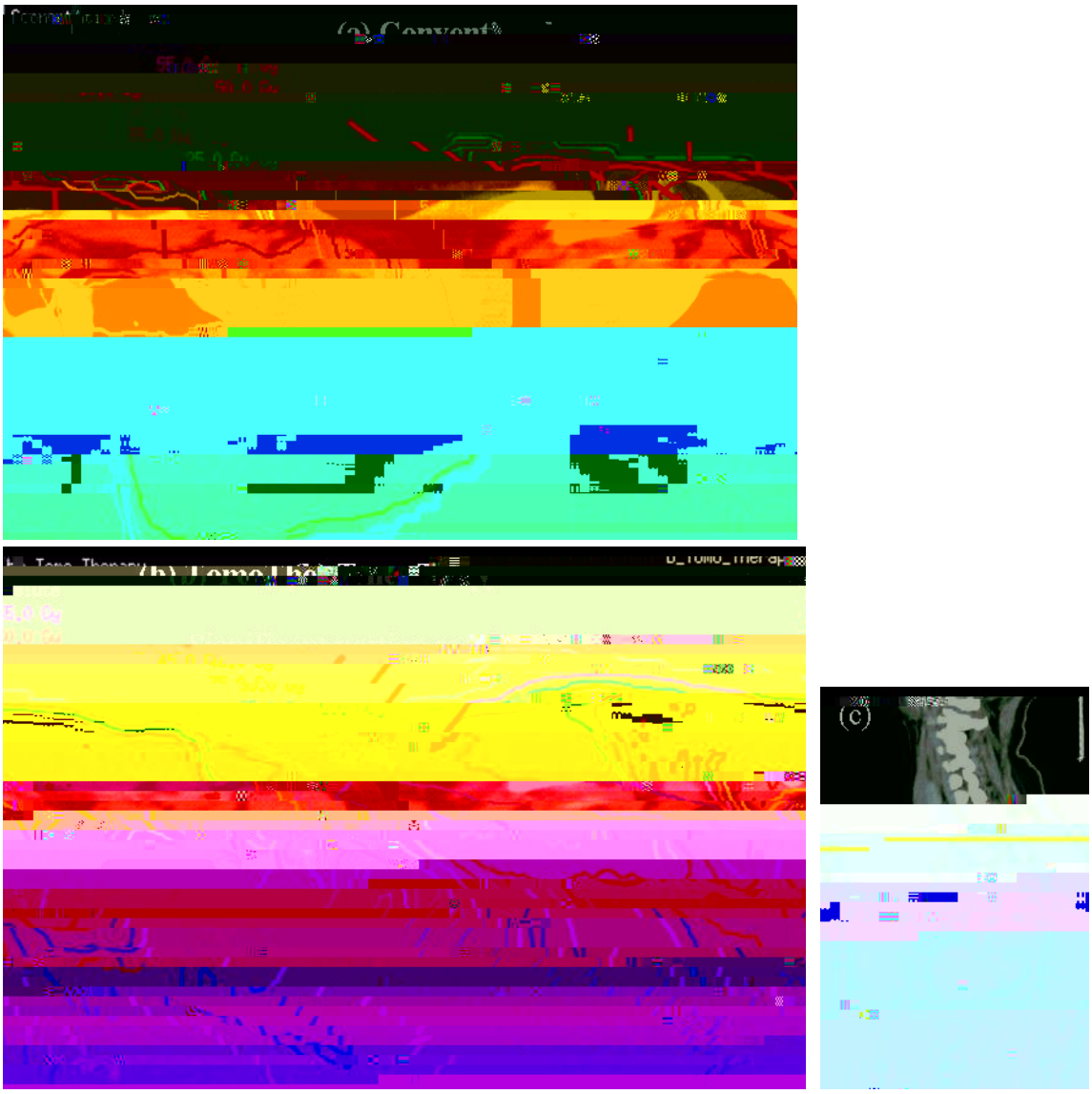


Figure 12. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the supraclavicular nodal region shown on sagittal view (c).

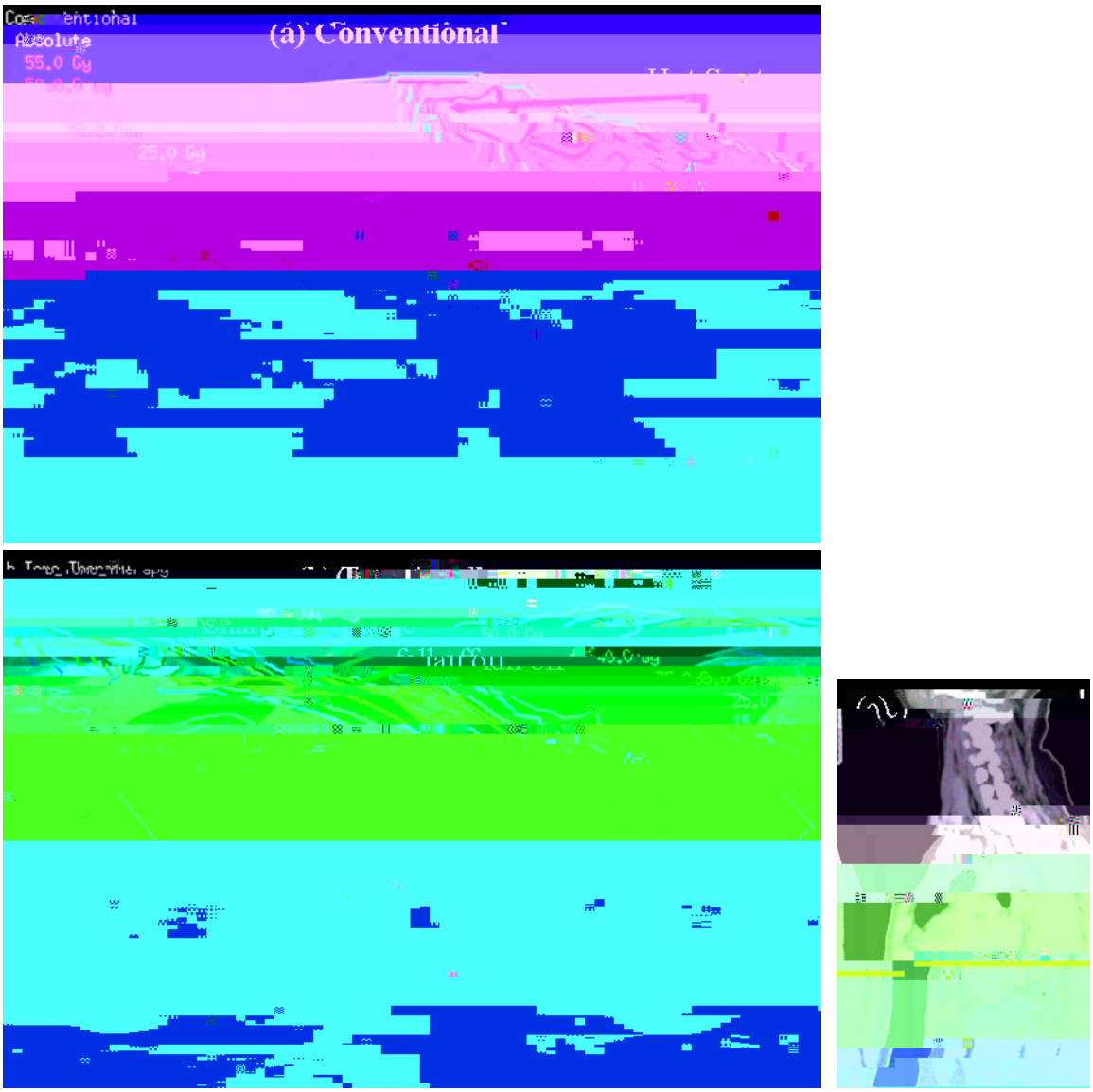


Figure 13. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the IMN region as shown on the sagittal view (c).

Figure 14 shows the isodose comparison between the conventional plan (Figure 14a) and the TomoTherapy plan (Figure 14b) on the transverse CT image slice near the inferior border of the CW PTV, and is delineated by the yellow line in sagittal midline CT image shown in Figure 14c. The yellow 45 Gy isodose line represents the th p250]250.685097

The conventional plan showed a sharper dose falloff than the TomoTherapy plan along the beam edges of the medial and the lateral CW of the conventional plan. Unlike the conventional plan, the TomoTherapy plan avoided irradiating the ipsilateral lung with high dose (45, 50, and 55 Gy). However, the TomoTherapy plan also showed a significant volume of tissue outside the PTV receiving low dose (5 Gy or more).

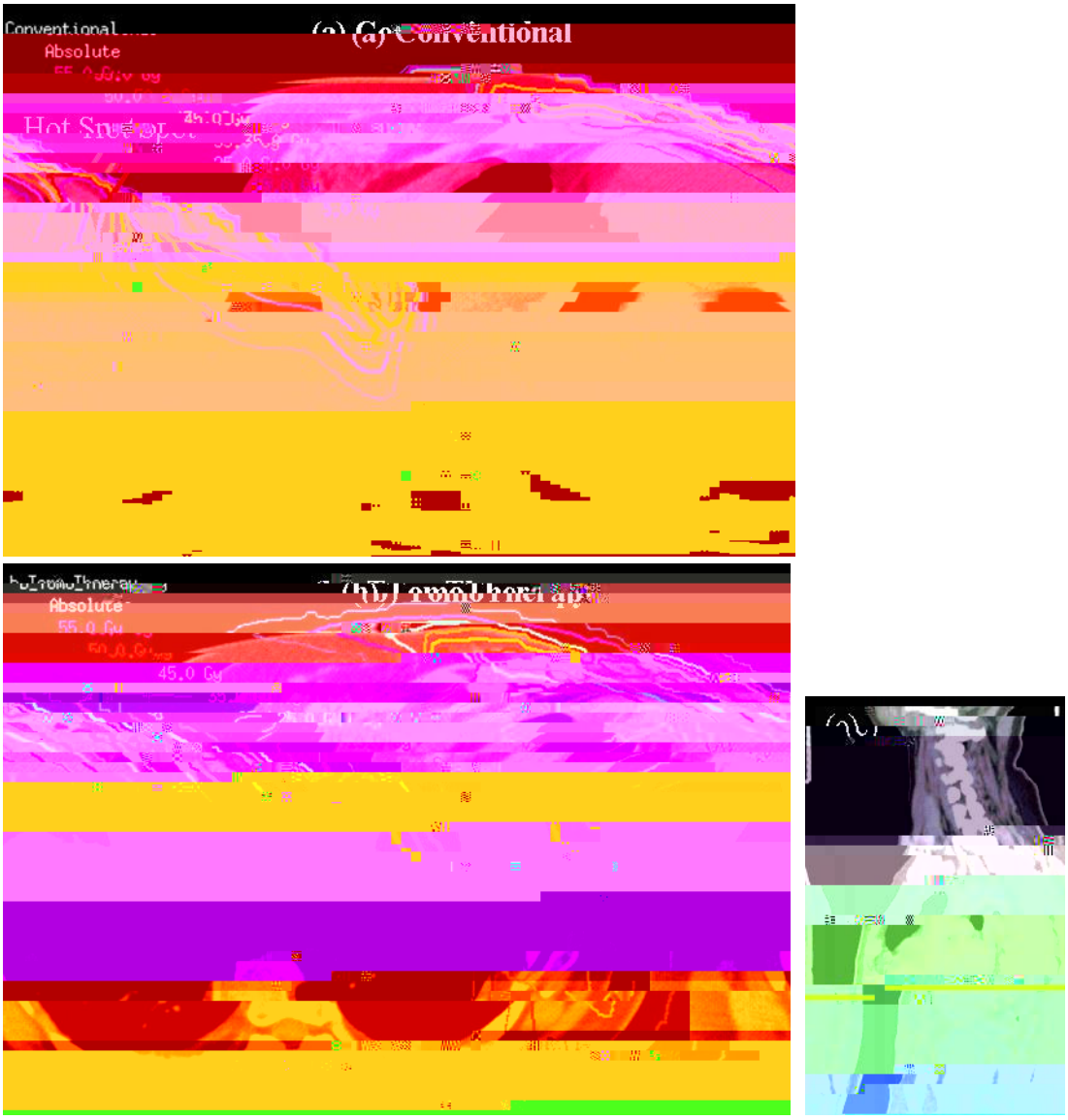


Figure 14. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the CW region as shown on the sagittal view (c).

are shown in Figure 15. The conventi l plan showed a

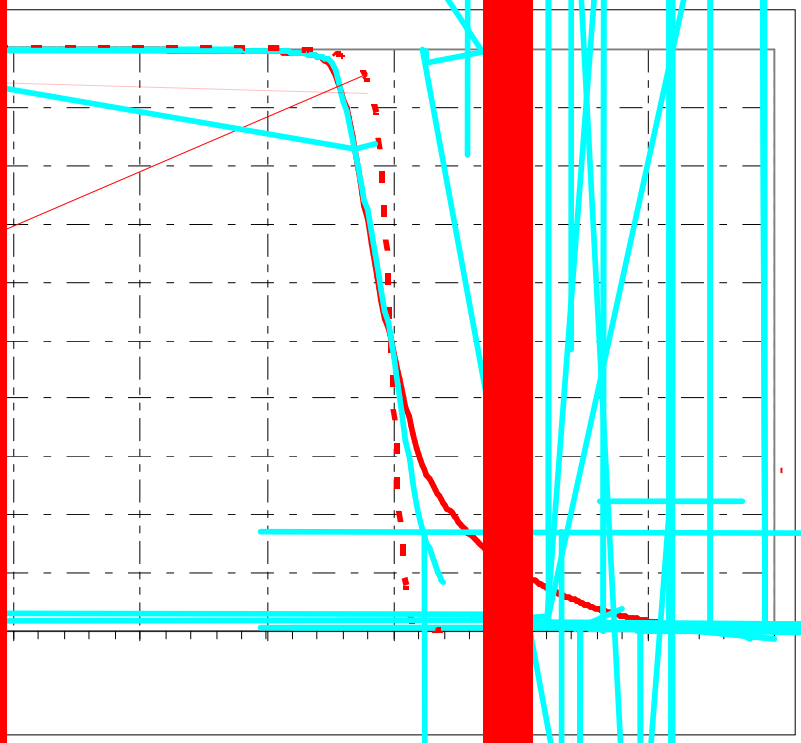
eceiving high dose created by the jun n of the medial and

herapy plan dose homogeneity was b r than the

the SCl/AX and CW PTVs. However, v dose (5 G y or

ume of the normal tissue not includin tical struct ures. The

ateral lung was 4.3 Gy, and the cross dose for the heart



TomoTherapy plan acceptable. After reviewing the dose distributions and DVHs for both plans, he ranked the TomoTherapy plan superior. The absence of hot and cold spots on

3.3.6. Heart

The heart volume receiving a dose above 30 Gy or more was very low (0.02% for the TomoTherapy plan and 0.9% for the conventional plan). The heart volume receiving 15 Gy or more was slightly higher on the TomoTherapy p

3.4. Patient Three

A 49-year old female was diagnosed to have a squamous cell carcinoma of the upper outer quadrant of the left breast, stage T2N1M0 carcinoma with 2 out of 10 lymph nodes positive with extra-nodal extension. The conventional electron beam PMRT plan had the following fields:

1. AP/PA 6 MV photon beam SCl/AX fields,
2. 9 MeV electron beam IMN field,
3. 9 MeV electron beam medial CW field, and
4. 9 MeV electron beam lateral CW field.

The prescription for the CW was 50 Gy in 25 fractions. The prescription for the SCl/AX was 45 Gy in 25 fractions.

3.4.1. Isodose Comparison

Figure 16 shows the isodose comparison between the conventional plan (Figure 16a) and the TomoTherapy plan (Figure 16b) on the transverse CT image slice in the region of the supraclavicular nodes delineated by the yellow line in sagittal midline CT image shown in Figure 16c. The yellow green 40.5 Gy isodose line represents the 90% prescription isodose line where the TomoTherapy plan was optimized to match the conventional plan. Compared to the conventional plan, the TomoTherapy plan showed small area covered by hot spot of 50 Gy (110% of the prescription dose).

The conventional plan showed a sharper dose falloff than the TomoTherapy plan along the beam edges of the parallel-opposed photon beams of the conventional plan. Greater dose restriction outside the supraclavicular PTV in the TomoTherapy plan during

volume of tissue outside the PTV receiving low dose (5 Gy or more). However, the TomoTherapy plan showed a greater dose gradient beyond the 40.5 Gy isodose line in

delineated by the yellow line in sagittal image shown in Figure 17c. The yellow 45 Gy isodose line represents the 90% prescription isodose line, where the TomoTherapy plan was optimized to match the conventional plan. The conventional plan showed a hot spot of 55 Gy (110% of the prescription dose) at the junction of the lateral and medial electron fields. Although in practice this hot spot is reduced (smeared) by moving the match line, this is not reflected in the conventional plan.

The conventional plan showed a sharper dose falloff than the TomoTherapy plan

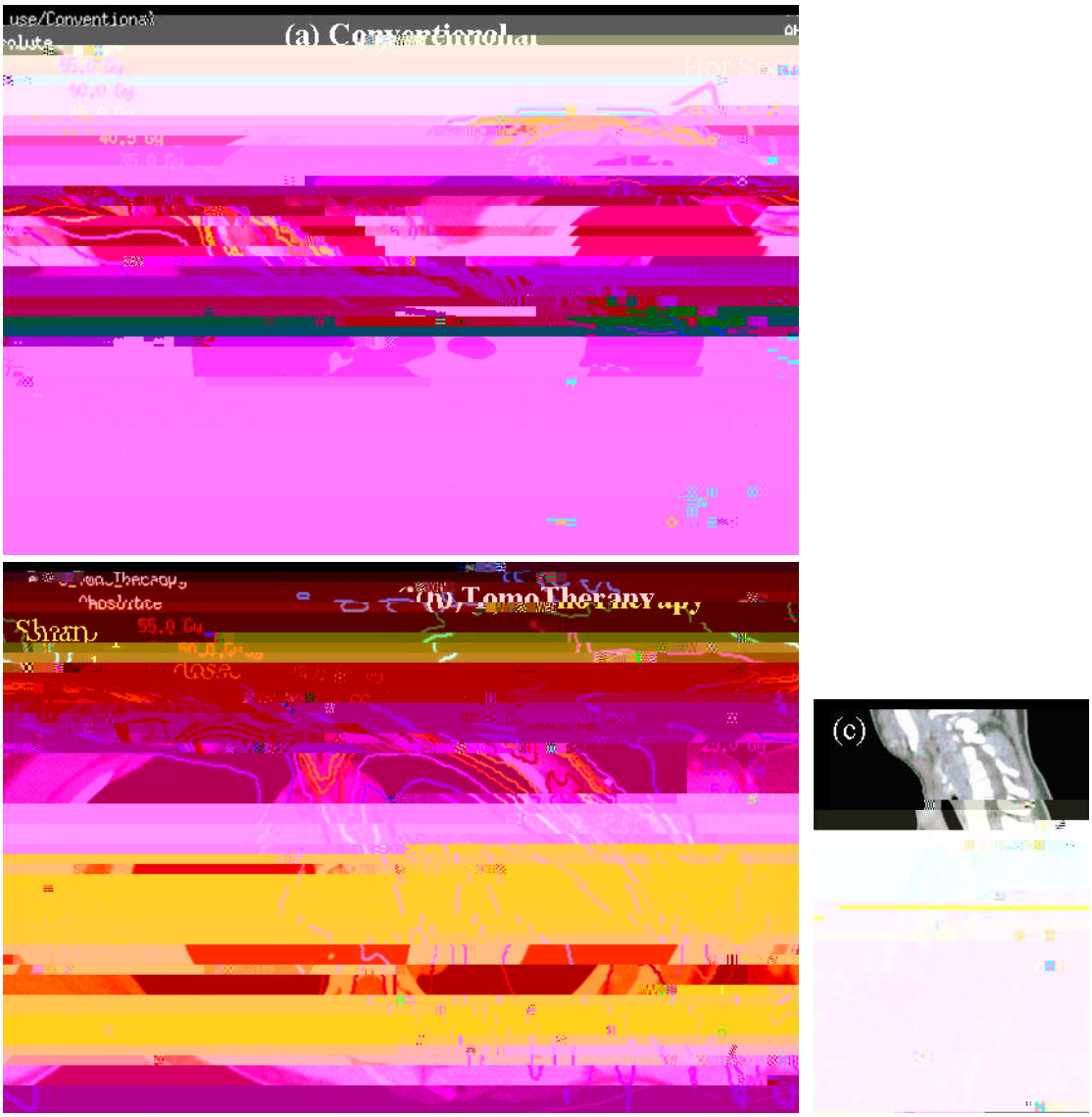


Figure 17. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the IMN region as shown on the sagittal view (c).

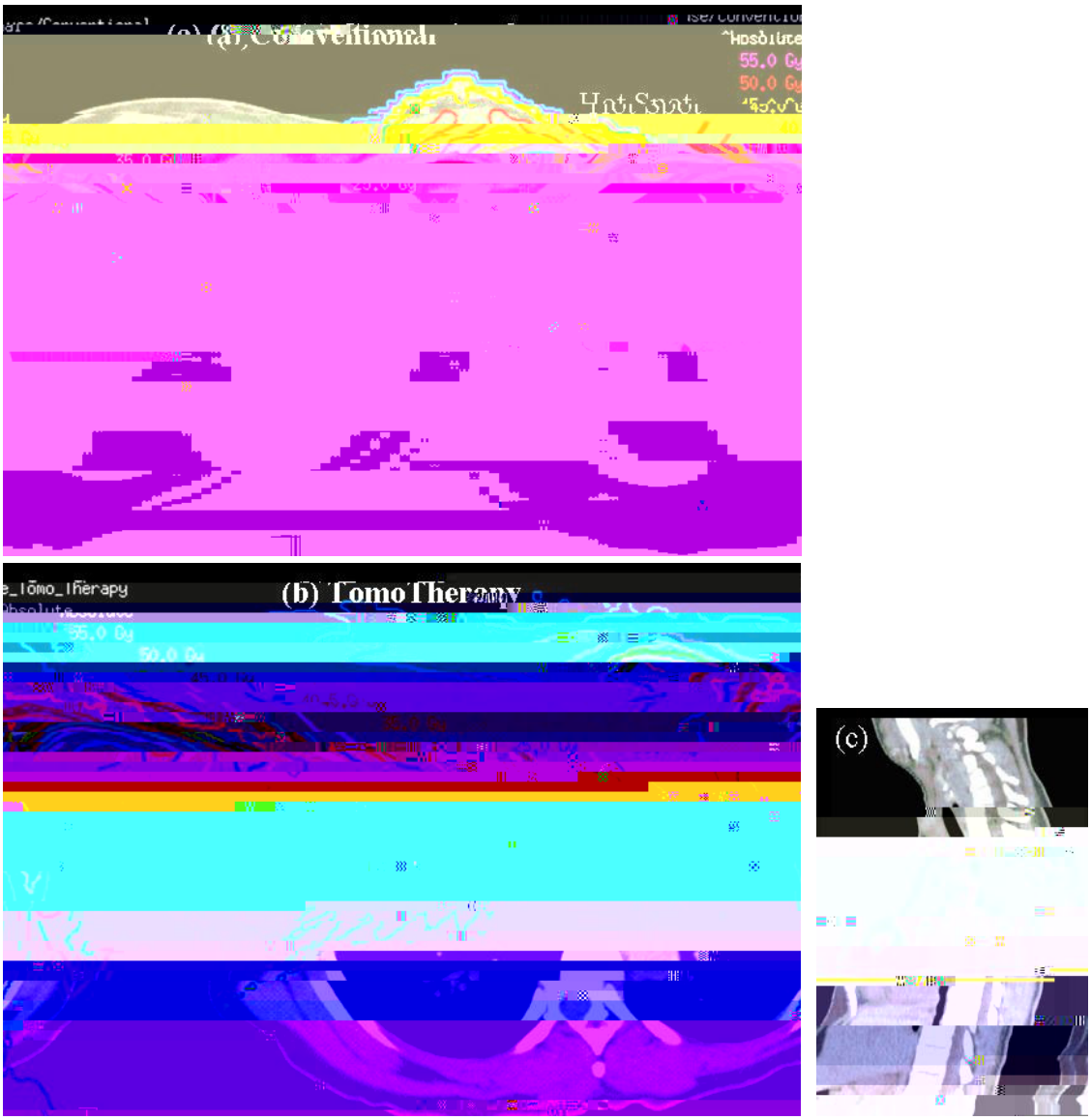


Figure 18. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the CW region as shown on the sagittal view (c).

The conventional plan showed a sharper dose falloff than that of the TomoTherapy plan along the beam edges of the medial and the lateral CW of the conventional plan. Greater dose restriction outside the CW PTV in the TomoTherapy plan during optimization might have resulted in a sharper dose falloff along the “beam edges” delineated by the conventional plan. The TomoTherapy plan also showed a significant volume of tissue outside the CW PTV receiving low dose (5 Gy or more). Both the

3.4.3. Radiation Oncologist Review

A radiation oncologist evaluated the clinical acceptability of both conventional and TomoTherapy plans and scored both plans acceptable. After reviewing the dose distributions and DVHs for both plans, he ranked the TomoTherapy plan superior. No

3.4.6. Heart

The heart volume receiving above 30 Gy or more was similar for both plans (2.2% for the TomoTherapy plan and 2.5% for the conventional plan). Also similar was the heart volume receiving 15 Gy or more (conventional plan = 12 % and TomoTherapy plan = 12.1 %). As shown on Figure 19 large volume of the ipsilateral lung received low dose (2.5 Gy) with the TomoTherapy plan compared to the conventional plan. A higher average heart dose ($\pm$ 1σ) was observed in the TomoTherapy plan (conventional plan = 5.6 $\pm$ 8.0 Gy and TomoTherapy plan = 7.1 $\pm$ 7.05 Gy). The NTCP values were the same for both plans (conventional plan = 0.004 and TomoTherapy plan = 0.004).

3.4.7. Contralateral Breast

The average contralateral breast dose ($\pm$ 1σ) was 2.1 $\pm$ 0.8 Gy for the TomoTherapy plan while 0.1 $\pm$ 0.1 Gy for the conventional plan. As shown on in Figure 19, relatively large volume of the contralateral breast was exposed to low dose (2 Gy) with the TomoTherapy plan compared to the conventional plan. Also, lW(t)-1.6164i2.341329( )0.34(l)-1.61644(W(t)-

)4.60185( )0.3

3.5. Patient Four

A 39 – year old female was diagnosed to have an infiltrating ductal carcinoma of the upper outer quadrant of the left breast, stage T3pN2aM0 carcinoma with 9 out of 12 lymph nodes positive with extra-nodal extension. The conventional electron beam PMRT plan had the following fields:

1. AP/PA 6 MV photon beam SCl/AX fields,
2. 12 MeV electron beam IMN field,
3. 9 MeV electron beam medial CW field, and
4. 9 MeV electron beam lateral CW field.

The prescription for the CW was 50 Gy in 25 fractions. The prescription for the SCl/AX was 48.25 Gy in 25 fractions.

3.5.1. Isodose Comparison

Figure 20 shows the isodose comparison between the conventional plan (Figure 20a) and the TomoTherapy plan (Figure 20b) on the transverse CT image slice in the region of the supraclavicular nodes delineated by the yellow line in sagittal midline CT image shown in Figure 20c. The yellow green 43.4 Gy isodose line represents the 90% prescription isodose line where the TomoTherapy plan was optimized to match the conventional plan. The conventional plan showed a hot spot of 55 Gy (110% of the prescription dose) in the medial, anterior portion of the dose distribution, whereas the TomoTherapy plan showed a lower hot spot of 50 Gy (104% of the prescription dose) in that region. Unlike the conventional plan, the TomoTherapy plan avoided irradiating the ipsilateral lung with high dose (45 Gy).

The conventional plan showed a sharper dose falloff than the TomoTherapy plan along the beam edges of the parallel-opposed photon beams of the conventional plan. The

TomoTherapy plan also showed a significant volume of tissue outside the PTV receiving low dose (5 Gy or more).

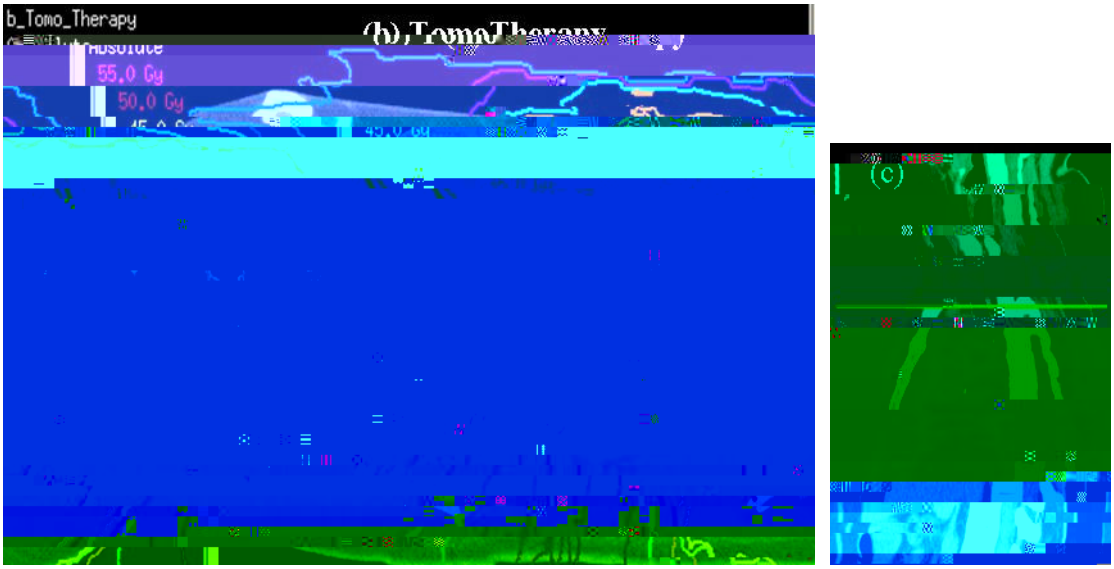


Figure 20. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the supraclavicular nodal region shown on sagittal view (c).

Figure 21 shows the isodose comparison for the conventional plan (Figure 21a) and the TomoTherapy plan (Figure 21b) on a transverse CT image slice in the region of the

plan was optimized to match the conventional plan. The Conventional plan showed a hot spot of 55 Gy (110% of the prescription dose) at the junction of the lateral and medial electron fields.

The conventional plan showed a sharper dose falloff than that of the TomoTherapy plan along the beam edges of the electron beams for the IMN and the lateral CW of the conventional plan. Higher dose near the aorta was observed in the TomoTherapy plan. The TomoTherapy plan showed a significant volume of tissue outside the PTV receiving low dose (5 Gy or more).

Figure 22 shows the isodose comparison between the conventional plan (Figure 22a) and the TomoTherapy plan (Figure 22b) on the transverse CT image slice near the

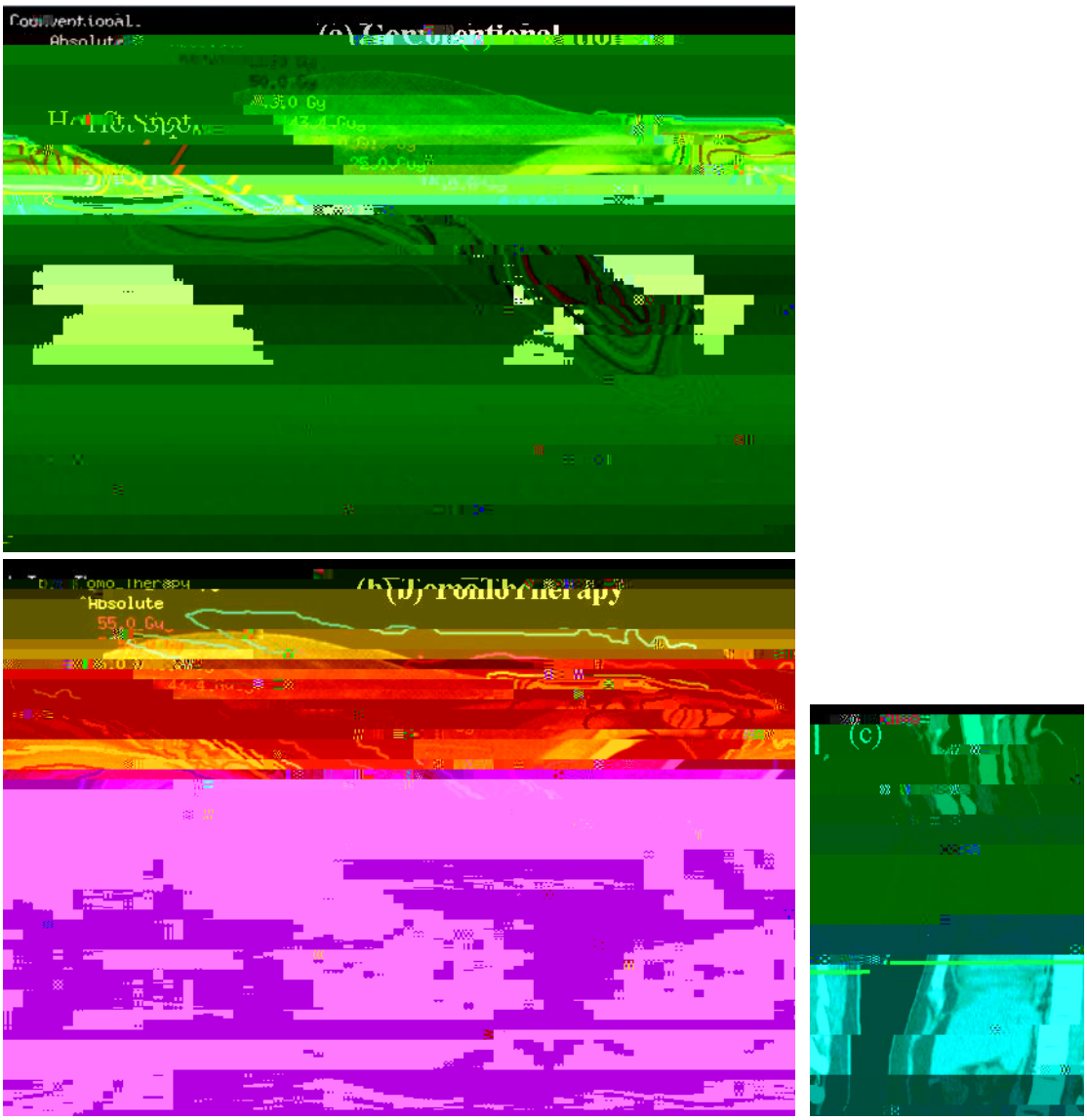


Figure 22. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the CW region as shown on the sagittal view (c).

conventional plan and was 3.0 Gy for the TomoTherapy plan. Even though, the CW PTV dose distribution showed better uniformity on the TomoTherapy plan, the TCP values were similar for both plans (conventional plan = 0.996 and TomoTherapy plan = 0.997).

3.5.5. Ipsilateral Lung

Compared to the conventional plan, the TomoTherapy plan avoided exposing the ipsilateral lung with high doses (45 Gy). However, as shown in Figure 23, a large volume of the ipsilateral lung received low dose (5 Gy or more) with the TomoTherapy plan. Similar values for $V20_{lung}$ was observed for both plans (conventional plan = 23.9% and TomoTherapy plan = 22.8%). The average ipsilateral lung dose ($\pm$ 1σ) was comparatively lower on the TomoTherapy plan (conventional plan = 13.3 $\pm$ 16.7 Gy and TomoTherapy plan = 12.7 $\pm$ 12.7 Gy). A relatively smaller NTCP value was observed for the TomoTherapy plan although both values were insignificant (conventional plan = 0.0117 and TomoTherapy plan = 0.0059).

3.5.6. Heart

The heart receiving dose above 30 Gy or more was reduced from 6.8% on the conventional plan to 4.1% on the TomoTherapy plan. The heart volume receiving 15 Gy or more was reduced from 17.1% on the conventional plan to 14.5% on the TomoTherapy plan. However, as shown in Figure 23, a large volume of the heart received low dose (2.5 Gy) with the TomoTherapy plan. Comparable average heart dose ($\pm$ 1σ) was observed in both plans (conventional plan = 8.5 $\pm$ 10.7 Gy and TomoTherapy plan = 9.1 $\pm$ 7.7 Gy). A lower NTCP value was calculated for the TomoTherapy plan (conventional plan = 0.020 and TomoTherapy plan = 0.007).

3.5.7. Contralateral Breast

Dose to the contralateral breast was significantly higher in the TomoTherapy plan than in the conventional plan. The average contralateral breast dose ($\pm$ 1σ) was 3.8 $\pm$ 2.8 Gy on the TomoTherapy plan while 0.7 $\pm$ 0.5 Gy on the conventional plan. As shown in Figure 23, a large volume of the contralateral brea

The prescription for the CW was 50 Gy in 25 fractions. The prescription for the SCl/AX was 45 Gy in 25 fractions.

3.6.1. Isodose Comparison

Figure 24 shows the isodose comparison between the conventional plan (Figure 24a) and the TomoTherapy plan (Figure 24b) on the transverse CT image slice in the region of

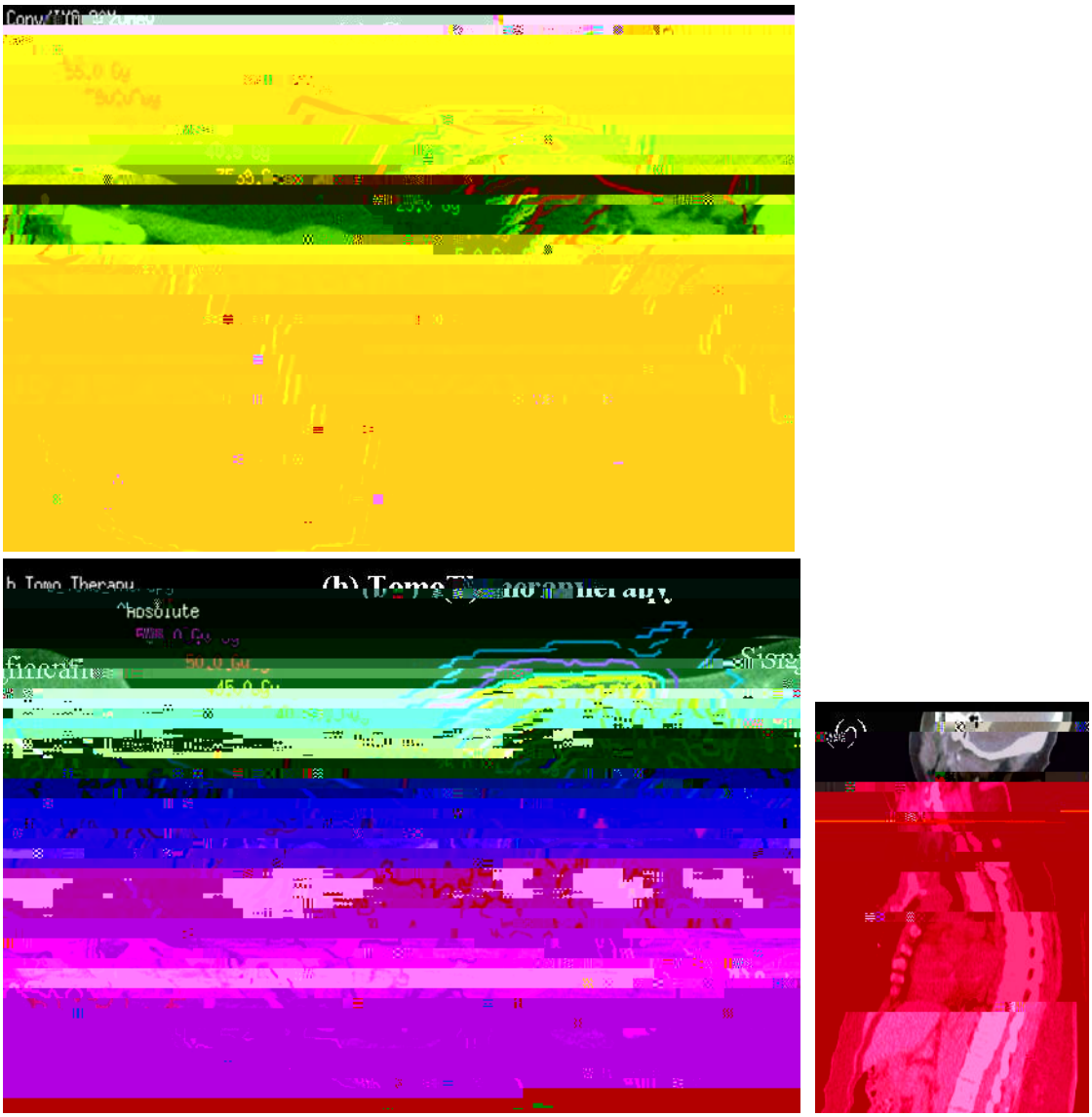


Figure 24. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the supraclavicular nodal region shown on sagittal view (c).

The conventional plan showed a sharper dose falloff than the TomoTherapy plan along the beam edges of the electron beams for the IMN and the lateral CW of the conventional plan. TomoTherapy showed more dose in the region of the aorta. Also, the

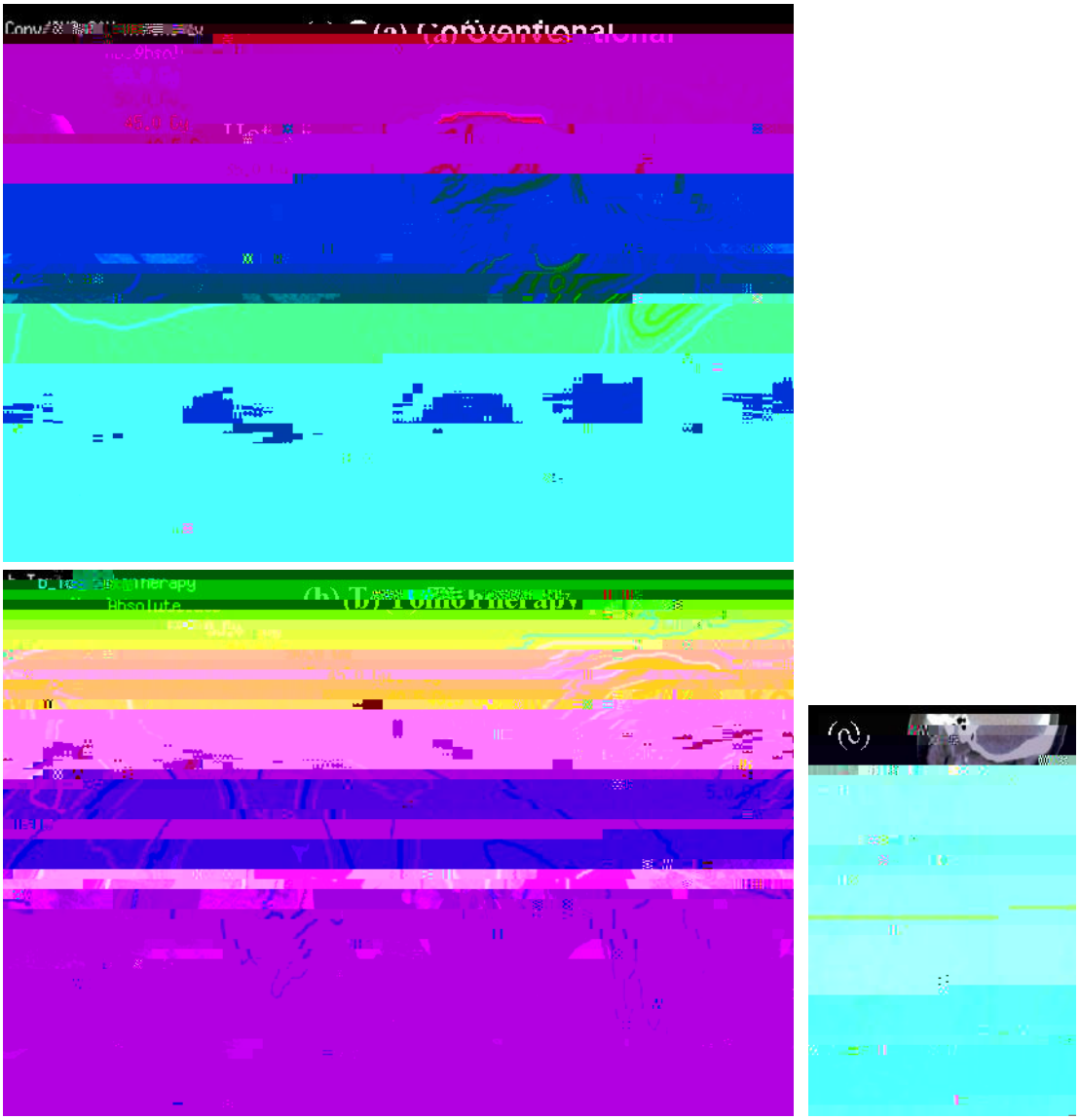


Figure 25. Transverse views of the conventional plan (a) and TomoTherapy plan (b) taken at the IMN region as shown on the sagittal view (c).

Figure 26 shows the isodose comparison between the conventional plan (Figure 26a)

3.6.2. DVH Comparisons

TomoTherapy plan acceptable. After reviewing the dose distributions and DVHs for both plans, he ranked the TomoTherapy plan superior. Better PTVs (CW and SCl/AX) coverage and fewer doses to the critical structure on the TomoTherapy plan was listed as a primary reason for preferring TomoTherapy plan over the conventional plan.

3.6.4. Chest Wall

The TomoTherapy plan showed improved dose homogeneity in the CW. The average CW dose ($\pm$ 1σ) was 50.4 $\pm$ 1.7 Gy on the TomoTherapy plan and 52.0 $\pm$ 5.2 Gy on the conventional plan. Dose irradiating 90% to 10% of the CW volume was 9.0 Gy on the conventional plan and was 3.5 Gy on the TomoTherapy plan. The TCP values were similar for both plans (conventional plan = 0.990 and TomoTherapy plan = 0.993).

3.6.5. Ipsilateral Lung

The TomoTherapy plan avoided exposing the ipsilateral lung with high doses (45 Gy). However, as shown in Figure 27, a large volume of the ipsilateral lung received low dose (5 Gy or more) with the TomoTherapy plan. Comparable $V20_{lung}$ was observed for both plans (conventional plan = 9.5% and TomoTherapy plan = 9.2%). The ipsilateral lung dose ($\pm$ 1σ) was lower for the TomoTherapy plan (conventional plan = 7.4 $\pm$ 10.2 Gy and TomoTherapy plan = 8.5 $\pm$ 8.0 Gy). A lower NTCP value was calculated for the TomoTherapy plan (conventional plan = 0.0001 and TomoTherapy plan = 0.0002).

3.6.6. Heart

In this patient the heart is not a proximal critical structure because the CW PTV is located on the right side of the patient's anatomy. The heart volume receiving above 30 Gy or more was similar for both plans (0.1% on the TomoTherapy plan and 0.4% on the conventional plan). The heart volume receiving 15 Gy or more was reduced from 4.1 % on the conventional plan to 1.9 % on the TomoTherapy plan. The average heart dose ($\pm$

1σ) was 5.2 ± 3.0 Gy on the TomoTherapy plan and 4.2 ±

Table 10. Summary of the radiation oncologist plan review

Patient	**Conventional (Conv.)**	**TomoTherapy (Tomo)**	**Conv. Vs. Tomo**	**Reason for preferring Tomo over Conv.**
1	Acceptable	Acceptable	Marginally* Superior	Better PTV coverage; absence of hot or cold spot
2	Marginally Acceptable	Acceptable	Superior	Absence of hot or cold spot
3	Acceptable	Acceptable	Superior	No comment

Table 11. Dmean (Gy) for PTV: CW (Average ± Standard deviation)

Patient	Conventional	TomoTherapy
1	50.7 + 6.0	49.6 + 0.9
2	51.4 + 6.1	49.9 + 1.1
3	52.4 + 7.0	49.7 + 1.9
4	54.0 + 7.5	50.4 + 1.5
5	52.0 + 5.2	50.4 + 1.7

Table 12. $D_{90\%} - D_{10\%}$ (Gy) for PTV: CW

Patient	Conventional	TomoTherapy
1	9.8	1.4
2	13.6	2.3
3	14.3	4.2
4	12.5	3.0
5	9.0	3.5

Table 13 lists the TCP values of the CW PTV for all patients. There was a slight, but insignificant difference in the calculated TCP values for CW PTV between the conventional and the TomoTherapy plans ($p = 0.11$).The average TCP value ($\pm 1\sigma$) on the conventional plan was 0.988 $\pm$0.007 and 0.994 $\pm$ 0.002 on the TomoTherapy plan.

Table 13. Calculated TCP values for CW PTV

Patient	Conventional	TomoTherapy
1	0.978	0.995
2	0.989	0.996
3	0.989	0.991
4	0.996	0.997
5	0.990	0.993

3.7.2. Lung

Table 14 lists the $V20_{lung}$ for the ipsilateral lung. There was a statistically significant difference in the ipsilateral lung volume receiving $\geq$ 20 Gy between the conventional and the TomoTherapy plans ($p = 0.05$). The average value ($\pm 1\sigma$) of the $V20_{lung}$ for the conventional plan was 21.5 $\pm$8.5 % and 17.6 $\pm$ 7.8 % for the TomoTherapy plan.

Table 16. Percent volume of the total lung (ipsilateral + contralateral) $\geq$ 20 Gy

Patient	Conventional	TomoTherapy
1	9.9	7.8
2	17.8	15.1
3	15.2	12.1
4	11.8	13.8
5	7.2	8.2

Table 17. Ipsilateral lung's calculated SCCP values

Patient	Conventional	TomoTherapy
1	0.020	0.033
2	0.019	0.025
3	0.014	0.023
4	0.019	0.024
5	0.032	0.041

Table 18 lists the calculated SCCP values for the total lung. There was significant differences in the SCCP between the total and the TomoTherapy plans ($p = 0.004$).The average SCCP value ($\pm$ 1σ) on the conventional plan was 0.032 $\pm$ 0.012 and 0.062 $\pm$

between the conventional and the TomoTherapy plans ($p = 0.14$). The average heart volume receiving dose above or equal to 30 Gy ($\pm 1\sigma$) was reduced from 2.7 $\pm$2.9 % on the conventional plan to 1.6 $\pm$ 2.0 % on the TomoTherapy plan.

Table 19. Percent volume of the heart receiving $\geq$

Age dependence effect of radiation induced breast cancer was ignored when calculating the SCCP values (Table 24) for the contralateral breast. There was statistically significant difference in the SCCP after radiotherapy between the conventional and the TomoTherapy plans ($p = 0.0001$). The average of the SCCP ($\pm 1\sigma$) was 0.002 ± 0.002 for the conventional plan and 0.016 ± 0.003 for the TomoTherapy plan.

Table 24. Calculated SCCP for the contralateral breast after radiotherapy

Patient	Conventional	TomoTherapy
1	0.0001	0.0178
2	0.0003	0.0125
3	0.0004	0.0131
4	0.0046	0.0183
5	0.0047	0.0191

3.7.5. Normal Tissue

Table 25 lists the percent volume of normal tissue receiving 5 to 25 Gy. There was a statistically significant difference between the rival plans in the percentage of normal tissue volume that received 5 to 25 Gy ($p = 0.002$). The overall average of on the conventional plan ($\pm 1\sigma$) was 23.4 ± 15.5 cm

Table 26 lists the SCCP values for normal tissue. There was a statistically significant difference in the SCCP values between the rival plans ($p = 0.001$). The average of the SCCP on the conventional plan ($\pm 1\sigma$) was 0.003 ± 0.002 and 0.010 ± 0.003 on the TomoTherapy plan.

Table 26. Calculated SCCP values for normal tissue

Patient	Conventional	TomoTherapy
1	0.003	0.012
2	0.002	0.008
3	0.002	0.007
4	0.004	0.009
5	0.006	0.014

Chapter 4
Discussions

The focus of this study was to show TomoTherapy could deliver dose distributions a radiation oncologist judges to be equal to or better than that of a conventional electron plan. Physical dose-volume and radiobiological metrics were calculated and used to evaluate the treatment plans in addition to the radiation oncologist's critique.

4.1. Similarities Between The TomoTherapy and Conventional Plans

Overall, the TomoTherapy plan was very similar to the conventional electron beam plan in treating the CW PTV while sparing critical structures adjacent to the CW PTV. There was no statistically significant difference in the CW TCP values between the TomoTherapy and conventional plans, although there was considerable difference in PTV dose homogeneity. The values for $V20_{lung}$ and NTCP for the ipsilateral lung were similar (i.e., no significant difference) between the two treatment plans, as was the values for $V15_{heart}$, $V30_{heart}$, and NTCP for the heart. From this study, one can assume with some degree of confidence that TomoTherapy is able to plan a PMRT that is as good as the conventional electron beam PMRT plan so far as TCP and NTCP are concerned.

4.2. Differences Between The TomoTherapy and Conventional Plans

As expected, the Tomotherapy plan showed better PTV dose uniformity compared to the conventional plan (Table 12). Dose uniformity was insured by giving a high importance to the PTVs (CW and SCl/AX), and as a result, the TomoTherapy plan produced a significantly more uniform dose distribution in the PTV. Also, the

field junctions added to the PTV dose inhomogeneity in the conventional plan. A difference in PTV dose homogeneity, mostly due to the abutting of the electron fields, were slightly over stated as the effect of edge feather were not included in the calculation.

On the other hand, the conventional plan successfully avoided irradiating the contralateral breast. In all five cases, the volume receiving 5 Gy or more was negligible (Table 23). In order to stop dose exposure to the contralateral breast, a higher importance factor was assigned compared to other critical structures during the optimization of the TomoTherapy plan. This helped reduce the dose to the contralateral breast; however, the nature of beam arrangements and modality made dose reduction difficult for the TomoTherapy. As a result, the average dose to the contralateral breast was higher compared to the conventional plan. The average for all five patients was increased from 0.4 Gy on the conventional plan to 2.95 Gy on the TomoTherapy plan. No excess breast cancer risk has been found among woman irradiated at age 40 years or older (Leeuwen et al. 2005*).* Boice et al, (1992) showed radiation exposure after the age of 45 years entails little, if any risk (relative risk, 1.01) of radiation-induced breast cancer for population of an average age of 51.7 years woman exposed with mean radiation dose to the contralateral breast be 2.82 Gy (maximum 7.10). Storm et al, (1992) also showed little if any risk (relative risk, 1.04) of radiation-induced breast cancer for population of an average age of 51 years woman exposed with mean radiation dose to contralateral breast estimated to be 2.51 Gy. Relative risk is ratio of the probability of the event occurring in the exposed group vs. the control (non-exposed) group. In the current study, the average age for the five patients was 53 years and the overall average mean dose was 2.95 Gy. Given the conclusions of the studies mentioned abov

accuracy of TomoTherapy dose delivery to the skin surface due to the effect of breathing

Chapter 6
Future Works

6.1. Additional Treatment Studies

Additional studies should be conducted to better compare conventional and TomoTherapy PMRT plans. These studies should include junction shift over the course of treatment should be modeled by the treatment planning system to reduce the hot spot seen in the dose distributions and DVHs. Also, sur

CW out of the PTV area for a fraction of the treatment, and therefore a margin would have to be added to the CW PTV to account for breathing. Unfortunately expanding the PTV into the air above the CW would have a negative impact on the optimization of beamlet fluence patterns near the skin unless the patient is scanned with bolus allowing expansion of the ROI above the skin.

6.4. Utility of Skin Collimation

Typically when the CW is treated with photon beams, bolus is applied to the skin of the CW to insure adequate skin dose. Such a procedure would be performed for PMRT on the TomoTherapy. I55O4193997(i(341663h)0.683878(e)4.60307(d)0.685097(85( )0.341939(T)1.83465(2

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24. Overgaard M., Jensen MB, Overgaard J**,** Hansen PS, Rose C, Andersson M, Kamby

Appendix A
Radiation Oncologist Evaluation of Treatment Plans

Date :
Patient:

a. Evaluate the clinical acceptability of plans (scale 1-5)

- How do you evaluate the **TomoTherapy plan**? Please circle one value that closely describes your observation.

1 2 3 4 5

Acceptable	1
Marginally acceptable	2
Indifferent	3
Marginally unacceptable	4
Unacceptable	5

- How do you evaluate the **Conventional plan**? Please circle

-

ii. Why do you prefer it? Is it,
    a. Better PTV coverage
    b. Less dose to the critical structure
    c. Less whole body dose
    d. other

c. Comment

Appendix B
Acronyms

ABR	American Board of Radiology
AX	axillary
CW	chest wall
CT	computed tomography
DVH	dose volume histogram
dDVHs	differential dose-volume histograms
FOV	field of view
IHD	ischaemic heart disease
ICRP	International Commission on Radiological Protection
IGRT	image-guided radiotherapy
IMRT	intensity-modulated radiotherapy
IMN	internal mammary chain
MVCT	mega-voltage computerized tomography system
MBPCC	Mary Bird Perkins Cancer Center
NTCP	normal tissue complication probability
OAR	organ at risk
PMRT	post-mastectomy radiation therapy
PTV	planning PTV volume
PWTF	partially wide tangent fields
RAR	region at risk
RHS	reverse hockey stick
ROI	region of interest
SCCP	secondary cancer complication probability
SCl	supraclavicular
SEER	Surveillance Epidemiology and End Results .44(l)-1.616446028(a)4.60307(r)3.40307(

Vita

Michael Ashenafi was born in Addis Ababa, Ethiopia, in 1979. He is the oldest son of Sissay Ashenafi and Birhan Abraham and has two brothers and one sister. He began his