

Scientific Paper

Dosimetric evaluation of VMAT automated breast treatment plans: Towards the establishment of an institutional plan acceptability criteria

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Abstract

Introduction: To evaluate the clinical suitability of the current facility-based treatment plan protocol in establishing acceptability criteria.

Material and methods: Automated Volumetric Arc Therapy (VMAT) treatment plans were retrospectively evaluated for intact breast and chest-wall cancer patients from January 2021 to January 2023.

Results: A total of 94 patients were planned and treated using automated contouring and VMAT planning technique. The number of patients planned and treated for intact breast and chest-wall were 41 (43.6%) and 53 (56.4%), respectively. The mean intact breast volumes for optimization (Brst_opt) receiving 95% and 105% of the prescribed doses were $92.80\% \pm 1.11$ and $1.54\% \pm 1.02$, respectively. Their corresponding mean chest-wall volumes for optimization (Chst_opt) were $90.65\% \pm 3.19$ and $2.28\% \pm 2.99$, respectively. For left-sided cases, the mean heart dose received was $4.61 \text{ Gy} \pm 1.76$ and $5.18 \text{ Gy} \pm 1.55$ for intact breast plans and that for chest-wall plans, respectively. The mean ipsilateral lung volume receiving 20 Gy of the prescribed dose was $12.22\% \pm 3.86$ and $13.19\% \pm 3.74$ for intact breast plans and chest-wall plans, respectively. For the Brst_opt and Chst_opt dose metrics were calculated; the mean homogeneity index (HI) was 0.14 ± 0.03 and 0.15 ± 0.04 , mean uniformity index (UI) was 1.09 ± 0.03 and 1.11 ± 0.03 , and mean conformity index (CI) were 0.92 ± 0.04 and 0.91 ± 0.04 , respectively.

Conclusions: The dosimetric evaluation shows a good dose distribution in the target volumes with minimal doses to the organs at risk (OAR). Assessment of the current data affirms the clinical usefulness of the facility-adopted protocol in achieving quality treatment plans for intact breast and chest-wall irradiations. The establishment of plan acceptability criteria will help achieve improved overall treatment outcomes.

Keywords: dosimetric indices; breast radiotherapy; plan quality; VMAT plan; acceptability criteria.

Introduction

Breast cancer, according to the current GLOBOCAN report, is the most prevalent cancer in the world and most frequent among African women in terms of incidence and mortality.¹ The treatment of breast cancer depends on the stage and consists of a combination of chemotherapy, surgery and radiation therapy to effectively manage it. For most patients, external beam radiation therapy (EBRT) is an essential component of their

treatment after breast-conserving surgery (BCS), known as lumpectomy (intact breast) or the total removal of the breast, known as mastectomy (chest-wall).² As compared to other cancers, curative doses used in breast cancer are relatively lower and do not require dose escalation for tumour control. A conventional dose fractionation schedule of 50 Gy in 25 fractions (2 Gy per fraction) over 5 weeks was prescribed. This was followed by a boost dose of 10 Gy delivered in 5 fractions to the tumour bed in selected patients. Key issues of concern that

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Authors' contribution:

A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

require critical attention are contour irregularities, dose planning process variations, risk of long-term toxicity and secondary carcinogenesis due to high doses to critical organs.³ Modern treatment planning and dose delivery techniques such as Volumetric Modulated Arc Therapy (VMAT) offer the freedom of delivering dynamic intensity-modulated radiotherapy with leaf sequencings of the multileaf collimator system to provide beam intensity modulations coupled with simultaneous gantry rotations to achieve better dose coverage to the tumour and reduction of doses to organs at risk. Treatment delivery with VMAT is faster, more efficient, and better dose conformity of the target, and additionally can provide differential dose distributions, allowing the simultaneous integrated boost (SIB) delivery.⁴ Results from EBRT breast cancer treatment survey conducted in Ghana⁵ identified certain variations in treatment planning guidelines, hence the need for this new facility to establish a standardized institutional-based protocol. Studies were carried out to focus on developing consistent breast-specific treatment planning guidelines through contouring and planning automation.^{6,7} This was to improve plan quality and maintain uniformity in treatment planning protocols within the facility for all breast cancer patients after breast-conserving surgery and mastectomy.⁸

With the majority of the chest-wall and intact breast tumour volumes assuming irregular shapes with critical OAR in close proximity to the tumour volumes, tailoring the dose distribution to conform to the target volume during treatment planning requires a very high level of competence and expertise due to these complexities.⁹ The conventional process is highly manual, requiring several iteration processes, fine-tuning and adjustments to produce an optimal plan worthy of approval for treatment delivery. Utilizing automated scripting eliminates unnecessary human errors and introduces constancy in the planning process.^{10,11} Evaluation of departmental protocol is key in assessing the clinical suitability of planned dose distribution and plan quality that is expected from a treatment plan. Systematic collection and analysis of clinical data is recommended in understanding the possible clinical outcome based on individual patient plans. Well-defined criteria for treatment plan acceptability should be established based on the results from the above-analyzed clinical data.^{12,13} This study tends to evaluate the automated VMAT departmental intact breast/chest-wall planning protocols and to establish plan acceptability criteria for the same.

For future studies, these established plan acceptability criteria would be quantified by developing institutional-based plan quality metrics (PQM) in assessing the quality of plans.^{14,15} With these PQMs, the automated intact breast and chest-wall plans can be compared and quantified to determine which plan has the highest plan quality.

Materials and Methods

The treatment plans of low-risk intact breast and chest-wall cancer patients treated with the VMAT technique at a new cancer centre over the first 2-year period were evaluated. All conserved breast and lumpectomy patients treated with a standard 50 Gy in 2 Gy per fraction within the time frame were selected. For each patient, data on their ages, the volume of the Plan Target Volume used for optimization (PTV_{opt}), ipsilateral lung volume, heart volume (for left-sided cases), contralateral lung volume and contralateral breast volume were recorded. For each VMAT treatment plan dose distribution, the minimum, maximum, mean and standard deviation of the Brst_{opt}/Chst_{opt}, ipsilateral lung, heart, contralateral lung and breast were determined. The DVHs were used to analyze the dose distribution in all contoured structures. For all PTV volumes used for optimization, their V_{90%}, V_{95%}, V_{100%}, and V_{105%}, (volume receiving 90, 95, 100 and 105 percentages of the PD, respectively) were evaluated from the DHV and recorded. Special attention was given to volumes receiving 95% (47.5 Gy) and 105% (52.5 Gy) of the prescribed dose. The PTV dose indices: Homogeneity index (HI), Uniformity index (UI), and Conformity index (CI) for the optimized tumour volumes were then calculated using **Equations 1, 2 and 3**.

Ethical clearance was applied for and approved (ECBAS 009/21-22) to retrospectively collect and analyze patient data. Informed consent for the study is not necessary since no direct involvement with any patient is required. However, permission was sought from the department to access its treatment plan database. All patient data were made anonymous by excluding their identities so they could not be linked back to any patient by another person. Data collected were also kept safe and were only accessible by the main investigator(s) during the research period.

Patients' characterization

Data of all ninety-four (94) intact breast and chest-wall cancer patients planned and treated from January 2021 to January 2023 were collected and retrospectively studied. These patients, as represented graphically in **Figure 1**, were planned using an automated VMAT treatment planning (inverse planning technique) script with a dose prescription of 50 Gy in 25 fractions. Bilateral intact breast and chest-wall patients were excluded from this analysis as well as patients with boost doses. The script for the intact breast and chest-wall VMAT planning automation was written using the Python programming language. The Pinnacle treatment planning system (TPS) was used for the VMAT treatment planning. It comes with three calculation options – fast convolution, adaptive convolution and collapsed-cone (CC) convolution. The adaptive convolution dose calculation algorithm was used in all treatment planning.

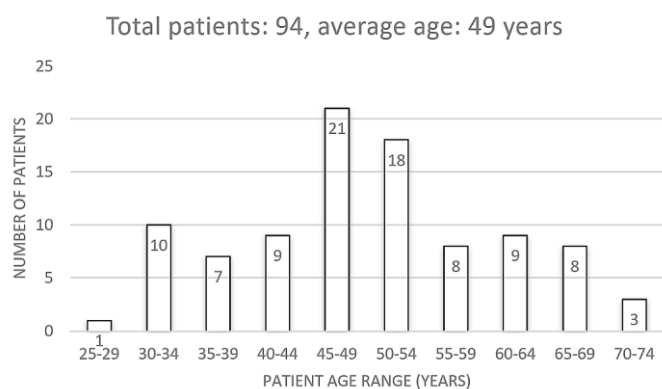


Figure 1. A plot of age distribution of total number of patients studied within the 2-year period

Patient dose planning CT simulation

A computed tomography (CT) pretreatment simulation scans are requested by the Radiation oncologist. For the scanning protocol at this facility, the patients were scanned in the supine position, head first into the scanner, with both arms raised above the head. Their arms were supported in a comfortable position with a breast board and a Kneefix placed under their knees. During the scan, only the upper body on the affected side was exposed from the waist up to maintain the patient's dignity. The head was positioned on an appropriate head rest and turned away in the opposite direction from the affected side of the breast. Radio-opaque wires were placed on the scar and on the surrounding breast for visualization on the radiograph. During simulation, with the aid of lasers, tattoos (permanent marks) were made on

the skin of the patient's thorax as reference points for setup. These tattoos were placed at the left and right laterals as well as on the anterior of the patient with the aid of small ball bearings (BB). Additionally, radiopaque wires were placed on the breast and chest-wall scar to guide the oncologists during target delineation. All patients are scanned with a MinFound ScintCare Blue 755 CT scanner (MinFound Medical Systems Co., Ltd, Zhejiang Province, P.R. China) using the institutional free breathing protocol with a slice thickness of 2.5 mm. The acquired CT Dicom dataset were then exported to the facility's local image server for onward upload/import into the automated software for contouring and to the TPS for planning.

Patient automated 3D volume contouring

The CT scan Dicom data were then automatically imported into ART-Plan (Version 1.11.3; TheraPanacea, Paris, France). ART-Plan is the facility's automated software used for contouring of all the associated OARs and the breast/chestwall volumes. As shown in **Figure 2**, the accuracy of this automatic contouring software for the breast is over 90% accurate, which may require minimal adjustments by the radiation oncologist. The software accurately contours the heart, ipsilateral lung, contralateral lung and contralateral breast volumes. The intact breast and chest-wall volumes were also contoured by the system, but this process requires the radiation oncologist to review them and approve the volumes for treatment planning. Only the approved 'RTStructure' set – clinical target volumes (CTVs) and OAR were then exported via the DICOM application to Pinnacle.

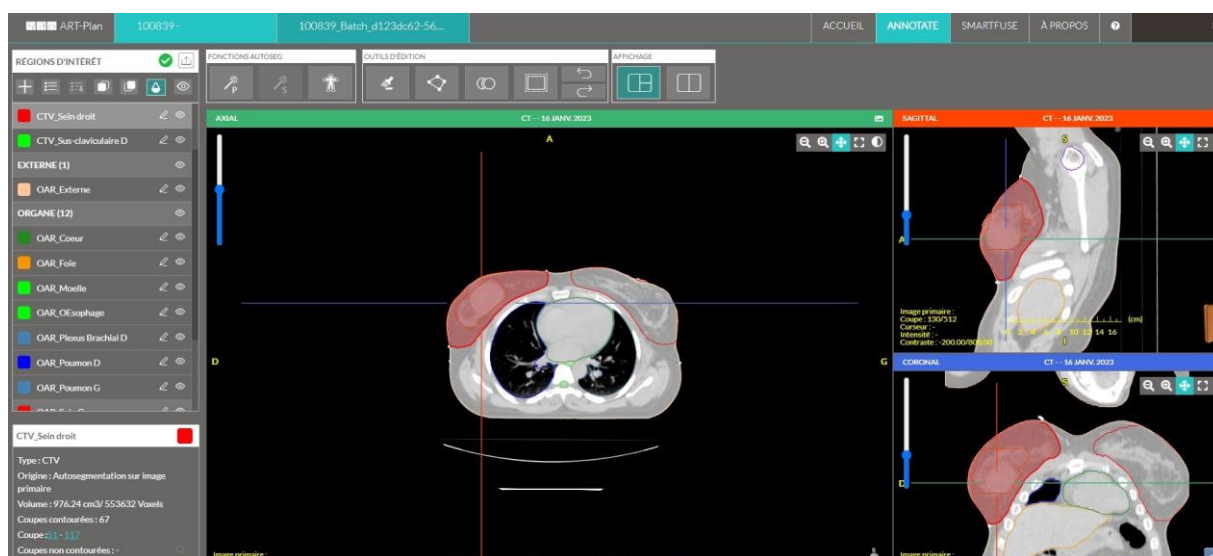


Figure 2. Axial, sagittal, and coronal views of an automated intact breast volume with its associated OARs done by the ARTPLAN software.

Patient automated VMAT treatment planning

The approved contoured patient dataset with all its associated reference points was then exported into the Pinnacle³ TPS (Version 16.2.1; Philips Medical Systems, Fitchburg, WI, USA). The correct CT number to the electron density convention table was selected. The couch top is excluded from the patient scan and laser coordinate system origin (represented by the 3 BBs) created at the laser center (referred to as the reference point R). The Python script program for treatment planning workflow automation started running when Pinnacle planning software was launched. From the script, the 'dosimetry' button is clicked, and the corresponding patient PTV is selected per the oncologist's prescription. The breast cancer type (intact breast or chest-wall) and its laterality are selected from the dropdown button. Automatically generated scripted plans were produced by clicking the script buttons. The automated process is streamlined as follows;

Creation of external/body volume, where skin padding of 0.3 cm or 0.5 cm was applied to create 'external-skin' volume depending on the extent of skin involvement. Next is the creation of the PTVs according to the facility's given CTV-PTV margins of 0 mm for intact breast and chest-wall and 7 mm for nodal involvement. The intact breast and chest-wall PTVs were also created by eliminating the intersected regions with the ipsilateral lung and heart volumes. Their corresponding PTV volumes used for optimization (PTV_opt) are created by subtracting the 'external-skin' volume from the PTV and any other regions of interest (ROI). The plan's isocenter, dose prescription and global dose volumes are created afterwards. Dose constraint objectives for the OARs with its optimization priorities, irradiation geometry (a 6 MV photon treatment beam placement and dynamic partial arc) and imaging fields (static open beam) were

created. Then, the dose constraint objectives for the PTVs with its set priorities were created according to the departmental protocol. The script for the DRR creation was activated to create the appropriate digital reconstructed radiographs (DRRs) filter settings to be used for MV imaging. The plan was optimized using two partial arcs (smart arc optimization), as shown in **Figure 3**, with an adaptive convolution dose computation algorithm. The Treatment planning system software used the inverse planning technique in designing breast plans. The software optimizer used the facility's set planning objectives for the PTV and organs at risk together with their set priorities to design the treatment planning accordingly. The optimizer only stops optimizing when all the criteria are met (best result per the given objectives). One or two more optimizations were done by the dose planner by changing the priorities to improve the plan's quality (reducing hotspots and further reducing doses to organs) after the initial optimization. The plan was then evaluated and approved by the radiation oncologist to be exported for patient-specific QA and onward treatment delivery on the Linac.

Patient radiation dose treatment delivery

The exported plan was imported into MosaiQ (Version 2.81, Elekta Inc., Sunnyvale, CA, USA), which is a record and verify system (RVS). A treatment verification plan was created for the patient using an Octavius 4D-phantom (PTW-Freiburg, Germany) in the TPS for patient-QA measurement. The measured doses with the phantom must pass the departmental/local gamma analysis criteria (3.0 mm distance-to-dose agreement and 3.0% dose difference) before the patient's first treatment session. A gamma index of more than 90% was considered to be acceptable to pass the plan for treatment.

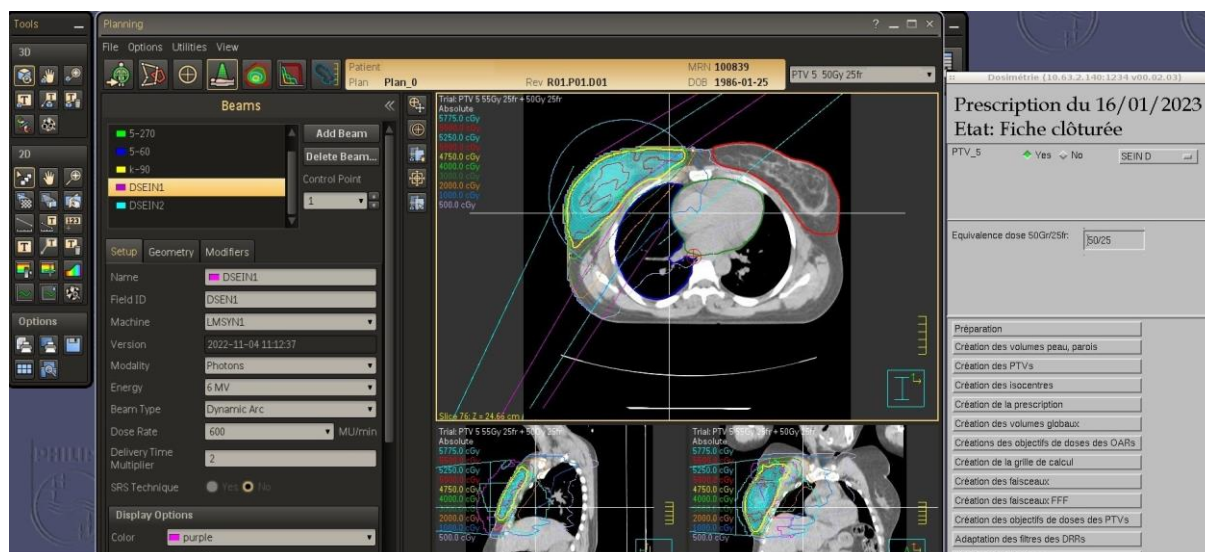


Figure 3. An automated VMAT intact breast plan using 2 partial arcs performed with a script programming running on a Pinnacle TPS. [Beam planning interphase]

During treatment, the patient was first positioned on the treatment couch, the same as during the CT simulation, with the aid of the reference markers/tattoos and the laser system. Electronic portal imaging device (EPID) attached to the treatment machine and iViewGT (Version 3.4.1, Elekta Inc., Sunnyvale, CA, USA) software was used for position verification before dose delivery. The portal images taken were automatically matched with their references according to departmental breast imaging protocol. The calculated offsets and resulting shifts after imaging were corrected before treatment. The RVS, which stores all beam parameters, was used to deliver the two partial arc VMAT treatments to the intact breast or chest-wall volumes.

Data analysis

Selected intact breast and chest-wall plan dosimetric data were collected from the TPS database and entered into a Microsoft Excel spreadsheet for analysis. The mean, maximum and minimum values together with their standard deviations were determined. The derived PTV and OAR dose-volume histogram (DVH) were also analyzed. The PTV volumes used for optimization and analysis were termed as 'Brst_opt' and 'Chst_opt' for intact breast and chest-wall, respectively.

Evaluation of OAR doses

The dose constraint for the heart was recorded by the percentage of heart volume that received 30 Gy ($V_{30\text{Gy}}(\%)$) as well as the heart volumes that received 5% ($V_{5\%(\%)}$) and 20% ($V_{20\%(\%)}$) of the prescribed dose. Per the departmental protocol, the mean doses (D_{avg}) to the heart volumes were also recorded.

For the ipsilateral lung, the dose constraint was recorded by the percentage of lung volume that received 20 Gy ($V_{20\text{Gy}}(\%)$) as well as the lung volumes that received 5% ($V_{5\%(\%)}$) and 20% ($V_{20\%(\%)}$) of the prescribed dose.

The other healthy breast was considered an organ at risk and protected during irradiation of the diseased intact breast and chest-wall. For all automated VMAT plans, the contralateral breast was contoured and its volume that received a maximum dose of 5 Gy were recorded.

Dosimetric indices evaluation

The derived DVH of the dose distributions were very useful in the evaluation of the dosimetric plan quality. Dose metrics, including homogeneity, uniformity and conformity, were calculated for both intact breast and chest-wall PTV volumes used for VMAT plan optimization.

The plan quality was quantitatively evaluated by calculating the homogeneity index (HI), uniformity index (UI) and conformity index (CI) for intact breast and chest-wall volumes used for optimization. Dose homogeneity and dose conformity are independent specifications of the quality of the absorbed

dose distribution. Dose homogeneity characterizes the uniformity of the absorbed-dose distribution within the target volume, while dose conformity characterizes the degree to which the high-dose region conforms to the target volume, usually the PTV_opt.¹⁶ The HI values are calculated using Yoon M. et al.'s formula¹⁷ as:

$$HI = \frac{(D_2 - D_{98})}{D_{PD}} \quad \text{Eq. 1}$$

Subsequently, the uniformity and conformity indexes were calculated respectively as:

$$UI = \frac{D_5}{D_{95}} \quad \text{Eq. 2}$$

$$CI = \frac{V_{RI}}{TV} \quad \text{Eq. 3}$$

where D_2 , D_5 , D_{95} , and D_{98} represent the doses received by 2%, 5%, 95%, and 98% volumes of the PTV_opt, respectively. D_{PD} is the prescribed dose of 50 Gy, V_{RI} is the volume of PTV_opt covered by the reference isodose line (95% isodose line using the ICRU-83), and TV is the target volume (Brst_opt and Chst_opt in this study). The closer the values of CI and UI are to 1 indicates greater conformity and uniformity, and values of HI closer to zero indicate greater homogeneity.

Results

The mean breast volume for optimization (Brst_opt) was $695.76 \text{ cm}^3 \pm 269.70 \text{ cm}^3$ (minimum of 379.75 cm^3 to maximum 1123.78 cm^3) and that for the chest-wall volume (Chst_opt) was $506.08 \text{ cm}^3 \pm 326.34 \text{ cm}^3$ (minimum of 216.88 cm^3 to maximum 913.27 cm^3). The mean breast separation for intact breast was $23.66 \text{ cm} \pm 3.92 \text{ cm}$ (ranging from 16.80 cm to 32.78 cm), and that for chest-all was $26.77 \text{ cm} \pm 3.37 \text{ cm}$ (ranging from 21.41 cm to 34.90 cm).

Table 1 and **Table 2** show the statistical analysis summary of the calculated HI, UI, and CI for all 94 patients' Brst_opt and Chst_opt volumes, respectively.

For the Brst_opt cases, the mean volume receiving 90% ($V_{90\% \text{ PD}}$), 95% ($V_{95\% \text{ PD}}$) and 105% ($V_{105\% \text{ PD}}$) of the prescribed dose were $97.32\% \pm 0.71\%$, $92.80\% \pm 1.11\%$ and $1.54\% \pm 1.02\%$ respectively. For Chst_opt cases, the mean volume receiving 90% ($V_{90\% \text{ PD}}$), 95% ($V_{95\% \text{ PD}}$) and 105% ($V_{105\% \text{ PD}}$) of the prescribed dose were $97.04\% \pm 1.59\%$, $90.65\% \pm 3.19\%$ and $2.28\% \pm 2.99\%$ respectively. Results for all optimized target volumes receiving various percentages of the prescribed 50 Gy dose are presented in **Table 3**.

The averages of the minimum (%Rx), maximum (%Rx) and mean dose(%Rx) deposited in the Brst_opt volume were $39.55\% \pm 9.64\%$ (19.77 Gy), $109.52\% \pm 1.40\%$ (54.76 Gy) and $99.43\% \pm 0.37\%$ (49.72 Gy) of the prescribed dose respectively. That for the Chst_opt volume were $22.92\% \pm 17.84\%$ (11.46 Gy), $108.61\% \pm 1.88\%$ (54.31 Gy) and $99.01\% \pm 1.52\%$ (49.51 Gy) percentage doses deposited, respectively.

Table 1. Summary of the statistical analysis of the homogeneity Index, the uniformity Index, and the conformity index for the Brst_opt for all the intact breast patients studied

	n	Minimum	Maximum	Mean (x)	Standard Deviation
Age (years)	41	25.00	61.00	51.03	12.35
Homogeneity Index	41	0.09	0.22	0.14	0.03
Uniformity Index	41	1.04	1.18	1.09	0.03
Conformity Index	41	0.81	0.96	0.92	0.04

Table 2. Summary of the statistical analysis of the homogeneity Index, the uniformity Index, and the conformity index for the Chst_opt for all the chest-wall patients studied

	n	Minimum	Maximum	Mean (x)	Standard Deviation
Age (years)	53	33.00	74.00	51.03	12.35
Homogeneity Index	53	0.09	0.24	0.15	0.04
Uniformity Index	53	1.06	1.19	1.11	0.03
Conformity Index	53	0.83	0.97	0.91	0.04

Table 3. Statistical analysis summary of patient PTV_opt volume receiving 90, 92, 95, 100, 105, 107, 108 and 110% of the prescription dose for both intact breast and chest-wall patients

Volume (cc) receiving the % of the PD	Breast volume for optimization				Chest-wall volume for optimization			
	Minimum	Maximum	Mean (x)	SD	Minimum	Maximum	Mean (x)	SD
	379.75	1123.78	695.76	269.70	216.88	913.27	506.08	326.34
V ₉₀ (%)	96.89	98.90	97.32	0.71	95.2	99.91	97.04	1.59
V ₉₂ (%)	95.92	97.89	96.05	0.90	92.67	97.01	94.88	1.77
V ₉₅ (%)	92.31	94.76	92.80	1.11	86.29	95.19	90.65	3.19
V ₁₀₀ (%)	48.67	50.72	49.49	0.84	41.05	45.21	43.89	1.73
V ₁₀₅ (%)	0.55	3.39	1.54	1.02	0.08	7.48	2.28	2.99
V ₁₀₇ (%)	0.00	0.56	0.25	0.01	0.00	2.56	1.02	1.05
V ₁₀₈ (%)	0.00	0.40	0.18	0.16	0.00	0.20	0.07	0.03
V ₁₁₀ (%)	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.00

Table 4. Summary of the statistical analysis of heart volume receiving 5%, 20% of the prescribed dose and volume receiving 30 Gy for both intact breast and chest-wall patients

Heart volume (cc)	Breast VMAT plan				Chest-wall VMAT plan			
	Minimum	Maximum	Mean (x)	SD	Minimum	Maximum	Mean (x)	SD
	453.12	689.47	586.00	51.73	414.64	771.32	630.21	110.62
V _{30 Gy} (%)	0.00	1.89	1.03	0.47	0.01	1.92	1.24	0.51
V _{5%} (%)	9.11	99.84	71.39	24.40	10.05	99.92	72.46	22.97
V _{20%} (%)	1.13	19.09	14.05	4.33	1.44	19.67	14.70	4.49
D _{min} (Gy)	0.26	2.21	1.04	0.68	0.38	2.53	1.39	0.60
D _{max} (Gy)	14.87	51.03	28.72	9.23	16.26	53.95	41.08	9.81
D _{avg} (Gy)	1.26	6.85	4.61	1.76	1.56	7.28	5.18	1.55

Table 5. Summary of statistical analysis of the ipsilateral lung volume receiving 5%, 20% of the prescribed dose and volume receiving 20 Gy for both intact breast and chest-wall patients

Ipst. lung volume(cc)	Breast VMAT plan				Chest-wall VMAT plan			
	Minimum	Maximum	Mean (x)	SD	Minimum	Maximum	Mean (x)	SD
	500.12	2139.49	799.83	276.01	511.89	2086.94	809.51	246.58
V _{20 Gy} (%)	1.78	17.16	12.22	3.86	2.12	18.54	13.19	3.74
V _{5%} (%)	46.71	99.08	78.11	14.68	47.05	99.28	73.71	14.80
V _{20%} (%)	10.71	39.77	26.25	8.65	11.53	40.41	26.94	9.02
D _{min} (Gy)	0.98	2.18	0.20	0.49	0.99	2.41	0.62	0.55
D _{max} (Gy)	47.00	50.69	40.73	2.30	48.14	51.63	41.05	2.12
D _{avg} (Gy)	9.03	12.25	4.15	2.06	9.52	12.88	5.21	2.28

Table 6. Summary of statistical analysis of the contralateral lung volume receiving 5 Gy for both intact breast and chest-wall patients

Cont. lung volume(cc)	Breast VMAT plan				Chest-wall VMAT plan			
	Minimum	Maximum	Mean (x)	SD	Minimum	Maximum	Mean (x)	SD
	668.15	2520.69	906.80	326.97	682.33	3003.07	899.04	414.25
V _{5 Gy} (%)	0.00	72.10	28.19	19.83	0.00	69.76	27.85	20.04
D _{min} (Gy)	0.05	1.84	0.55	0.40	0.04	1.90	0.59	0.75
D _{max} (Gy)	2.61	49.51	16.97	12.21	2.53	48.69	14.72	12.56
D _{avg} (Gy)	0.42	8.10	3.57	2.15	0.39	7.55	3.95	3.09

Table 7. Summary of statistical analysis of contralateral breast volume for both intact breast and chest-wall patients

Cont. breast volume(cc)	Breast VMAT plan				Chest-wall VMAT plan			
	Minimum	Maximum	Mean (x)	SD	Minimum	Maximum	Mean (x)	SD
	329.44	2139.49	743.23	356.07	394.37	2047.03	754.15	400.41
V _{5 Gy} (cc)	0.00	799.72	134.30	137.60	0.00	769.71	127.57	120.32
D _{min} (Gy)	0.00	1.50	0.56	0.29	0.00	1.39	0.51	0.23
D _{max} (Gy)	0.58	7.64	3.66	2.87	0.51	7.28	3.58	2.05
D _{avg} (Gy)	0.24	4.92	2.06	1.97	0.20	4.99	1.95	1.81

The mean heart volumes for patients treated with intact breast and chest-wall were $586.00 \text{ cm}^3 \pm 51.73 \text{ cm}^3$ (ranging from 453.12 cm^3 to 689.47 cm^3) and $630.21 \text{ cm}^3 \pm 110.62 \text{ cm}^3$ (ranging from 414.64 cm^3 to 771.32 cm^3) respectively. **Table 4** captures the statistical analysis of heart volume dose parameters for both the intact breast and chest-wall plans.

For the intact breast cases, the averages of the minimum (%Rx), maximum (%Rx) and mean dose(%Rx) within the heart volume were $2.69\% \pm 1.84\%$ (1.04 Gy), $61.80\% \pm 18.46\%$ (28.72 Gy) and $9.52\% \pm 3.52\%$ (4.61 Gy) respectively. That for the chest-wall cases were $2.78\% \pm 1.20\%$ (1.39 Gy), $82.17\% \pm 19.62\%$ (41.08 Gy) and $10.36\% \pm 3.09\%$ (5.18 Gy) percentage doses deposited, respectively.

The mean ipsilateral lung volumes for all patients treated with intact breast plan and chest-wall plan were $799.83 \text{ cm}^3 \pm 276.01 \text{ cm}^3$ (ranging from 500.12 cm^3 to 2139.49 cm^3) and $809.51 \text{ cm}^3 \pm 246.58 \text{ cm}^3$ (ranging from 511.89 cm^3 to 2096.94 cm^3) respectively. **Table 5** shows the dosimetric analysis of the ipsilateral lung volumes for both the intact breast and chest-wall VMAT plans treated with 50 Gy dose in 25 fractions.

The mean contralateral lung volumes were $906.80 \text{ cm}^3 \pm 326.97 \text{ cm}^3$ (ranging from 668.15 cm^3 to 2520.69 cm^3) and $899.04 \text{ cm}^3 \pm 414.25 \text{ cm}^3$ (ranging from 682.33 cm^3 to 3003.07 cm^3) for intact breast and chest-wall cases, respectively. The dose constraint was a percentage of the contralateral lung volume receiving 5 Gy (V_{5Gy}(%)). The dosimetric analysis for the contralateral lung volume is captured in **Table 6** for both the intact breast and chest-wall VMAT plans. **Table 7** below captures the statistical analysis of the contralateral breast volume dose parameters for both the intact breast and chest-wall plans. The mean doses received by the contralateral breast were less than 5 Gy for both intact breast and chest-wall cases.

In **Table 1** and **Table 2**, these dose metrics are presented for 41 intact breast plans and 53 chest-wall plans. The mean HI, UI, and CI for intact breast (Brst_opt) volume were 0.14 (ranging

from 0.09 to 0.22), 1.09 (ranging from 1.04 to 1.18), and 0.92 (ranging from 0.81 to 0.96), respectively. The corresponding values for chest-wall (Chst_opt) volume were 0.15 (ranging from 0.09 to 0.24), 1.11 (ranging from 1.06 to 1.19), and 0.91 (ranging from 0.83 to 0.97), respectively.

Discussions

This study was to evaluate the dose distribution of VMAT treatment plans used in treating patients with breast cancer (intact breast and chest-wall) at a new cancer facility over the first two years and establish plan acceptability criteria. Dosimetric estimation for 94 breast patient treatment planning data was done, and facility-based plan acceptability criteria were developed. The dosimetric estimation was done for intact breast volume and chest-wall volume contoured for VMAT planning optimization as well as the OAR structures. The PTVs for optimization were created by eliminating the intersected PTV regions with the ipsilateral lung and heart volumes. These volumes presented the actual intact breast and chest-wall target volumes used for dosimetric analysis purposes. This prevented the overestimation of the target volumes, which would have affected the dosimetric analysis of the PTVs. The minimum, maximum, mean and standard deviations were determined from the PTV volumes and OARs for intact breast and chest-wall. Subsequently, dose metrics were evaluated from the DVH for the two PTV_opt volumes.

The optimized PTV volumes receiving 95% (V_{95% PD}), and 105% (V_{105% PD}) of the PD were of great importance to this study in establishing the plan acceptability criteria. According to the recommendation for level 2 reporting by the ICRU report 83¹⁶, at least 95% of the treatment volume must receive at least 95% of the prescribed dose. A study by Adnani et al.¹⁸ has also shown that minimizing the breast volume receiving 105% of the PD leads to better treatment outcomes. From the studied data, the average of the mean percentage dose (%Rx) and maximum

percentage dose (% $R_{x_{max}}$) in the intact breast volume were $99.43\% \pm 0.37\%$ (49.72 Gy) and $109.52\% \pm 1.40\%$ (54.76 Gy), respectively. Those for the chest-wall volumes were $99.01\% \pm 1.52\%$ (49.51 Gy) and $108.61\% \pm 1.88\%$ (54.31 Gy) percentage doses, respectively. This shows that, on average, the target volumes received more than the 95% prescribed dose recommended by ICRU. However, the maximum percent doses were also higher than the recommended value of 105% of the prescribed dose. This has the risk of increased treatment complications and should be minimized as recommended for better treatment outcomes. The absorbed dose coverage was better with the intact breast volumes than the chest-wall as expected. This was mainly due to the smaller volume of the chest-wall as compared to that of the intact breast. The smaller the chest-wall volume, the lesser the dose coverage unless bolus are used to increase coverage. From the dosimetric data analysis, 95% of the prescribed dose (47.5 Gy) covered an average intact breast volume of $92.80\% \pm 1.11$ and an average chest-wall volume of $90.65\% \pm 3.19$. These average values did not meet the 95% dose coverage to 95% of PTV per departmental protocol. However, this does not necessarily mean all studied patients had inferior PTV dose coverage, **Table 3** shows a maximum volume coverage of approximately 95% for Brst_opt and over 95% for Chst_opt. Based on currently established plan acceptability criteria, further improvement in the department's breast treatment planning optimization criteria needs to be developed to increase overall average dose coverage for the PTV volume to at least 95%. PTV_opt volumes for future breast treatment plans can be evaluated along these mean PTV_opt values to ensure consistency in treatment planning. According to the results, $1.54\% \pm 1.02$ and $2.28\% \pm 2.99$ of the mean Brst_opt and Chst_opt volumes received 105% or more of the prescribed dose, respectively. This restricted all the mean PTV_opt volumes receiving a hot spot of 105% ($V_{105\%PD}$) of the prescribed dose to less than 3%. Based on the results as shown in **Table 3**, $V_{105\%}$ can be further minimized to less than an average of 1% for better outcomes in breast radiation treatments.

The critical OAR of importance for patients being treated with cancer in the left breast is the heart. Increased risk of late effect of high radiation to the heart has been established from big data collection and longer follow-up analysis. Results from such a study recorded a minimal heart dose exposure similar to the heart dose constraint as established by our department (mean dose of 7.5 Gy). For the intact breast cases, the average dose (D_{avg}) received by the heart was $4.61 \text{ Gy} \pm 1.76$ (min: 1.26 Gy and max: 6.85 Gy). The average heart dose (D_{avg}) for the chest-wall cases was 5.18 ± 1.55 (min: 1.56 Gy and max: 7.28 Gy). A study conducted by Darby et al.³ for over 2,000 women treated with radiotherapy for breast cancer over a period of 43 years found a direct correlation between the average heart dose and major coronary incidents. They concluded that the baseline risk of cardiac mortality increases linearly by 7.4% per 1 Gy of the average heart dose and takes effect within 5 years of treatment

and for at least the next 20 years. Results, as captured in **Table 4**, show that the intact breast VMAT planning produces plans with lower heart doses than the chest-wall VMAT plans. This may be due to lesser breast tissues and thinner target volumes presented by many chest-wall cases. Another OAR dose constraint objective used in analyzing the absorbed dose received by the heart was the volume receiving 30 Gy ($V_{30Gy(\%)}$). In addition, the heart volumes that received 20% ($V_{20\%(\%)}$); that is 10 Gy of the prescribed dose were equally recorded and analyzed. An average heart volume of $1.03\% \pm 0.47$ and $1.24\% \pm 0.51$ for the intact breast VMAT plan and chest-wall VMAT plan, respectively, received 30 Gy. These values were below the constraints set by the department of $V_{30Gy} < 5\%$. Similarly, the mean heart volume that received $V_{20\%}$ of the PD was $14.05\% \pm 4.33$ and 14.70 ± 4.49 for intact breast and chest-wall VMAT plans, respectively. These values were below the departmental dose constraint of $V_{20\%(\%) < 20\%$. Based on these current results, the department's VMAT breast treatment planning can be used in achieving heart dose values of 10 Gy and 30 Gy to less than 20% and 5% of the heart volumes, respectively. The same acceptability criteria can be established using the average dose of less than 7.5 Gy received by the heart volumes.

Due to the close proximity of the lung volume to the breast and chest-wall target volumes, it tends to receive the highest dose during radiation treatment delivery. Per the department protocol for the VMAT planning technique, both the ipsilateral lung (main OAR of interest) and contralateral lung volumes are contoured. For parallel organs such as the lung, ICRU 83 report¹⁶ recommends more than one dose-volume specification to be considered for its reporting. So for the Ipsilateral lung, volumes receiving 20 Gy ($V_{20Gy(\%)}$) and 30 Gy ($V_{30Gy(\%)}$) and average doses (D_{avg}) received were collected and analyzed for both VMAT plans. The institutional-based automated VMAT planning objective criteria required the ipsilateral lung volume that received 20 Gy and 30 Gy to be less than 30% and 20%, respectively, while an average dose of 12.5 Gy was set as the constraint dose objective for the lung volume. From the dosimetric analysis, the intact breast VMAT and chest-wall VMAT plans gave an average dose of $4.15 \text{ Gy} \pm 2.06$ (min: 9.03 Gy and max: 12.25 Gy) and $5.21 \text{ Gy} \pm 2.28$ (min: 9.52 Gy and max: 12.88 Gy) respectively to the ipsilateral lung volume. The mean lung volume receiving a dose of 20 Gy was $12.22\% \pm 3.86$ and $13.19\% \pm 3.74$ for the intact breast and chest-wall VMAT plans, respectively. These results indicate that there is no significant difference in ipsilateral lung dose between the two VMAT techniques. From **Table 5**, it was observed that both VMAT plans delivered acceptable doses to the ipsilateral lung volumes according to the departmental plan objective.

For the contralateral lung, $V_{5 \text{ Gy}(\%)}$ were also recorded and analyzed. A study by Hall and Wu¹⁹ holds the view that the VMAT breast plan improves dose conformity of the target but at the cost of increased low doses to the contralateral lung and contralateral breast, which may result in an increased risk of

secondary malignancy. The results shown in **Table 6** agree with their findings, as low doses were recorded in the lung volume for both VMAT plans. Minimum, maximum and mean low doses of 0.05 Gy, 1.84 Gy and $0.55 \text{ Gy} \pm 0.40$ were recorded for intact breast VMAT plan, and corresponding low doses of 0.04 Gy, 1.90 Gy and $0.59 \text{ Gy} \pm 0.75$ were recorded for chest-wall VMAT plan. The mean lung volume that received 5 Gy was $28.19\% \pm 19.83$ for the intact breast plan and $27.85\% \pm 20.04$ for the chest-wall plan. Based on these plan acceptability criteria, similar mean ipsilateral and contralateral lung volumes can be achieved using the departmental optimization criteria. However, the recorded low doses in the contralateral lung volume can be addressed with further improvement to the current VMAT planning optimization criteria.

Another important organ at risk to be considered during VMAT breast planning and dose delivery was the contralateral breast. A study²⁰ analyzed patient data (from 1985 to 1999) treated with two opposing tangential beams with an average dose of 1.3 Gy to the contralateral breast. Younger women less than 40 years were observed to be at risk, especially those who received 1 Gy more to their contralateral breast, having a 2.5-fold increased risk of developing secondary breast cancer. This excess risk was not so for women over 40 years of age. A similar study by Boice et al.²¹ also revealed an increase in risk of secondary breast cancer from 2.7% to 11.1% for women less than 45 years. Results from our dosimetric evaluation show a mean dose of less than 5 Gy to the contralateral breast for both intact breast and chest-wall VMAT plans. The facility-based objective criteria used for the contralateral breast dose was a dose maximum (D_{\max}) of 5 Gy. From **Table 7**, the average D_{\max} for the intact breast plan was $3.66 \text{ Gy} \pm 2.87$ and $3.58 \text{ Gy} \pm 2.05$ for the corresponding chest-wall plan. Based on these current mean contralateral breast acceptability criteria, the department's VMAT breast treatment planning optimization can be used in achieving a contralateral breast dose maximum of 5 Gy or less. All these challenges, when not addressed, might present long-term cardiac mortality, symptomatic pneumonitis, secondary malignancy and sometimes disease recurrence²².

The aim of dosimetric plan evaluation was to assess the plan's quality using qualitative and/or quantitative approaches. Each plan was quantitatively assessed by calculating its HI, UI and CI for the PTV_opt for all 94 patients. These dose metrics derived from the DVH serve as a very useful and objective method of quantifying the plan's quality with respect to target coverage. Values of CI and UI closer to one indicate greater conformity and uniformity, and that of HI closer to zero indicate greater homogeneity. Results from our evaluation show relatively superior average dose conformity, uniformity and homogeneity

in the Brst_opt and Chst_opt volumes. The mean HI for the Brst_opt and Chst_opt were 0.14 ± 0.03 and 0.15 ± 0.04 respectively. This demonstrates greater uniformity of the absorbed dose distribution within the various target volumes. The mean UI for the Brst_opt and Chst_opt were 1.09 ± 0.03 and 1.11 ± 0.03 , respectively. The mean CI values were 0.92 ± 0.04 and 0.91 ± 0.04 for the Brst_opt and Chst_opt, respectively. The dose conformity demonstrates a greater degree to which the high-dose regions conform to the various target volumes. A detailed summary of the calculated HI, UI and CI values are represented in **Table 1** and **Table 2** for all patients studied in this research. VMAT plans for the optimized intact breast volumes exhibited superior mean dose metrics than those for the chest-wall volumes. However, the department's VMAT breast planning optimization criteria produced smaller hotspots while maintaining improved dose coverage (conformity) and dose uniformity throughout the intact breast and chest-wall volumes.

Conclusion

A facility-based plan acceptability criteria was established using two years of patient data from breast treatment plans dosimetric analysis. These plan evaluations exhibited acceptable dose distributions in the intact breast and chest-wall target volumes with minimal doses to critical organs. The evaluation of patient data affirms the clinical usefulness of the facility's breast planning protocol in achieving quality treatment plans for intact breast and chest-wall irradiations. The clinical implementation of the established plan acceptability criteria for intact breast and chest-wall treatment plan approval can produce clinically acceptable treatment plans while eliminating variations in plan acceptability. The established facility plan acceptability criteria should be periodically evaluated using improved dose reduction strategies to further improve overall treatment plan quality.

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