Journal of Radiotherapy in Practice

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Retrospective analysis of portal dosimetry pre-treatment quality assurance of hybrid IMRT breast treatment plans

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Original Article

Cite this article: Koo M, Darko J, and Osei E. (2021) Retrospective analysis of portal dosimetry pre-treatment quality assurance of hybrid IMRT breast treatment plans. *Journal of Radiotherapy in Practice* **20**: 22–29.
doi: 10.1017/S1460396920000072

Received: 9 December 2019
Revised: 19 January 2020
Accepted: 21 January 2020
First published online: 27 February 2020

Key words:
breast cancer; EPID; IMRT QA; portal dosimetry; quality assurance

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Abstract

Background: The purpose of this study is to evaluate the effectiveness and sensitivity of the Varian portal dosimetry (PD) system as a quality assurance (QA) tool for breast intensity-modulated radiation therapy (IMRT) treatment plans.
Materials and methods: Four hundred portal dose images from 200 breast cancer patient IMRT treatment plans were analysed. The images were obtained using Varian PortalVision electronic portal imaging devices (EPIDs) on Varian TrueBeam Linacs. Three patient plans were selected, and the multi-leaf collimator (MLC) positions were randomly altered by a mean of 0·5, 1, 1·5 and 2 mm with a standard deviation of 0·1 mm on 50, 75 and 100% of control points. Using the improved/global gamma calculation algorithm with a low-dose threshold of 10% in the EPID, the change in gamma passing rates for 3%/3 mm, 2%/2 mm and 1%/1 mm criterion was analysed as a function of the introduced error. The changes in the dose distributions of clinical target volume and organ at risk due to MLC positioning errors were also analysed.
Results: Symmetric and asymmetric breast or chest wall plan fields are different in delivery as well as in the QA. An average gamma passing rate of 99·8 ± 0·5 is presented for 3%/3 mm symmetric plans and 96·9 ± 4·5 is presented for 3%/3 mm asymmetric plans. An average gamma passing rate of 98·4 ± 4·3 is presented for 2%/2 mm symmetric plans and 89·7 ± 9·5 is presented for 2%/2 mm asymmetric plans. A large-induced error in MLC positioning (2·0 mm, 100% of control points) results in an insignificant change in dose that would be delivered to the patient. However, EPID portal dosimetry is sensitive enough to detect even the slightest change in MLC positioning error (0·5 mm, 50% of control points).
Conclusions: Stricter pre-treatment QA action levels can be established for breast IMRT plans utilising EPID. For improved sensitivity, a multigamma criteria approach is recommended. The PD tool is sensitive enough to detect MLC positioning errors that contribute to even insignificant dose changes.

Introduction

Intensity-modulated radiation therapy (IMRT) is a treatment technique that delivers radiation to the treatment target using fields with non-uniform radiation fluence. Compared to 3D conformal radiation therapy, IMRT can generate more complex dose distributions due to the use of smaller beamlets allowing more control of dose distribution that conform closely to the target volume and improving dose homogeneity and conformity within the target.[1] Due to the complexity and uniqueness of IMRT treatment plans, patient-specific pre-treatment quality assurance (QA) is necessary to ensure that the linear accelerator can deliver the planned dose distribution calculated in the treatment planning system (TPS). There are currently several techniques available for patient-specific pre-treatment QA including the use of a 2D ion chamber array, 2D diode array, ArcCHECK™ (Sun Nuclear Corp., Melbourne, FL, USA), MAPCheck™, Delta4™ (ScandiDos AB, Uppsala, Sweden) and MatriXX™ (IBA Dosimetry GmbH, Schwarzenbruck, Germany). The use of electronic portal imaging devices (EPIDs) is, however, a novel method of pre-treatment IMRT verification.[2,3] In this method, high-resolution digital images taken with the EPID can be compared with the predicted portal dose calculated in the TPS. The dedicated ARIA™ portal dosimetry (PD) review workspace within the Eclipse™ TPS is used to evaluate the agreement between the predicted and the measured images to ensure that the planned dose distribution for the patient is deliverable by the machine and, therefore, the dose delivered to the patient will agree with the planned dose.[3,4]

The use of EPID for patient-specific QA is gradually becoming common in cancer centres due to its simplicity and set-up.[4] When comparing the measured and predicted dose using the EPID method, parameters such as the dose difference (DD), distance-to-agreement (DTA) and

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gamma (γ) index are used.[5] In low-dose gradient regions, the calculated and measured doses can be compared using the DD. However, in high-dose gradient regions, DDs are relatively unimportant since small spatial error (in either calculation or measurement) can result in large DD. In these cases, the DTA is a better parameter to judge the goodness of the measured portal prediction.[5] As a result, using both DD and DTA evaluations simultaneously in a composite analysis leads to a more accurate verification of the dose distribution. In the method developed by Low et al.,[5] the quality index (γ-index) is used as a numerical measure of the agreement or disagreement between measured and calculated dose distributions. For a selected passing criterion of DD and DTA (e.g., 3%, 3 mm), a γ-index is generated with a pass–fail criterion: if $\gamma \leq 1$ the calculation passes but if $\gamma > 1$ the calculation failed.[5] The percentage of the field that satisfies the defined gamma criterion (DD, DTA) is defined as the percentage gamma passing (%GP) rate and is used to determine the level of agreement between the measured dose and the predicted dose.

At our institution, we use a hybrid IMRT technique for breast cancer patients' treatment plans. The technique uses both open and optimised beams to produce a homogeneous dose distribution in the breast or chest wall. For treatments involving the supraclavicular nodes, a mono-isocentric technique is used consisting of a single isocentre for all three or four fields. In these situations, the isocentre is located at the junction of the tangential and supraclavicular fields.[6] Treatment plans using the hybrid IMRT technique provide an improved conformal dose coverage of the target while minimising doses to organ at risk (OAR) such as the heart, lungs and the contralateral breast.[6,7] However, disadvantages to this technique include tangential field size limitation and high-dose gradient in the junction region.[6] The PD QA technique is used to verify all breast IMRT plans based on a γ passing rate of 95% at 3 mm, 3% with a global improved gamma criterion.

The aim of this study is to evaluate the effectiveness of using the EPID as a QA tool for breast IMRT plans. In addition, we also tested the sensitivity of the tool to detect errors in multi-leaf collimator (MLC) positioning and relate the possible change in dose distribution resulting from the positional errors. This study is based on the analyses of portal dose images from breast cancer patients' IMRT plans. Previous studies have investigated delivery errors such as MLC position,[8–10] gantry angle,[9,10] couch shift[11] and dose.[10] The results of this study will establish possible new guidelines and action levels in EPID QA of breast IMRT plans.

Materials and Methods

We retrospectively re-evaluated 400 portal dose images from 200 breast cancer patients treated using the integrated Varian solution for all aspects of treatment (planning, delivery and QA analysis) at our centre. Patients' treatment plans were categorised into four groups based on left or right intact breast treatment or left or right chest wall treatment. Overall, there were 50 patients randomly selected in each of the four categories: right breast (BRER), left breast (BREL), right chest wall (CHWR) and left chest wall (CHWL). The patient plans were delivered on Varian TrueBeam linear accelerators (Varian Medical Systems, Palo Alto, CA, USA) equipped with a 120 MLC and one of two integrated amorphous silicon (aSi) EPIDs—Varian PortalVision aS1000: a $40 \times 30\ cm^2$ flat-panel, with a matrix of $1{,}024 \times 768$ pixels and 0·392 mm pixel resolution or Varian aS1200: a $43 \times 43\ cm^2$ flat-panel, with a matrix of $1{,}190 \times 1{,}190$ pixels and 0·336 mm pixel resolution. The mechanical calibration of the exact arms was performed by our in-house service personnel, and the EPID dosimetry configuration and calibration was done by medical physicists.

Breast Treatment Planning

All treatment planning was accomplished using institutional protocols and was performed using the Eclipse TPS, version 13.6 (Varian Medical Systems). The details of patients positioning, CT simulation, target volume delineation and treatment planning are discussed by Osei et al.[7] In summary, all structure segmentations (planning target volume, body, lung and heart contours) were accomplished using institutional protocol. The treatment planning is accomplished using a hybrid IMRT technique which consists of an open and an optimised field for both the medial and lateral fields. The open fields are usually weighted to deliver about 50–70% of the prescription dose depending on the breast size and the optimised field used to deliver the remaining 50–30% of the prescription dose.

Portal Dosimetry QA

The details of the PD QA processes including the portal dose prediction, portal dose measurements, portal dose analysis and calibration of the EPID are explained by Maraghechi et al.[4]; however, a brief summary for breast QA is given below. Daily QA is performed on all linacs to ensure consistency in output, symmetry and flatness.

Portal dose prediction and measurements

The Portal Dose Image Prediction Algorithm version 13.6 (Varian Medical Systems) was used to calculate the expected fluence from EPIDs for all plans at a source-to-imager distance of 100 cm. The verification plans were delivered on TrueBeam Linacs using the integrated image acquisition mode. For efficient and optimal usage of the EPID for breast IMRT plan QA, all beams are delivered at a static zero gantry angle and collimator angle of 90° (to ensure the image will fit to the active area of the EPID).

Portal dose analysis

The dedicated ARIA™ Portal Dosimetry Review workspace within the Eclipse™ TPS was used to evaluate the agreement between predicted and measured images. Dosimetric analysis of the PortalVision dose images was performed via Varian Portal Dosimetry Version 13.6. The gamma index concept in the PD system was used to quantify the results with the assumption that if the agreement between the predicted and measured images are within set accepted tolerances, then the treatment plan is dosimetrically deliverable by the treatment machine. The absolute gamma analyses were performed to obtain the %GP, γ_{max}, γ_{ave}, DD_{max} and the DD_{ave}. We used the improved gamma calculation algorithm in the Portal Dosimetry Version 13.6 which allows for interpolating between neighbouring pixels when searching. We investigated the gamma passing rate with DTA and DD tolerances at 3·0 mm/3·0%, 2·0 mm/2·0% and 1·0 mm/1·0%. In addition, the images were renormalised relative to the spatial centre of the irradiated area and the analyses were repeated for the renormalised images.

EPID QA Sensitivity Test

We further investigated the sensitivity of the gamma index analysis to determine its capability to detect MLC positioning errors. Three

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treatments plans: one from each of the BRER, BREL and CHWR categories was selected for this investigation. Deliberate errors, with a mean of 0·5, 1·0, 1·5 and 2·0 mm and a standard deviation of 0·1 mm, were applied on all active MLC leaves, and for 50, 75 and 100% of randomly selected control points in the treatment plans. The dosimetric impact of the deliberately introduced errors on the clinical target volume (CTV) and OAR dose distributions was evaluated and compared to the change in %GP.

MLC leaf position errors

Using a modified version of an in-house Python program described by Maraghechi et al.,[12] errors were deliberately introduced to the MLC positions of the selected treatment plans. For each breast IMRT plan, the original (error free) DICOM file was exported from the TPS and the Python program was used to introduce deliberate errors to the MLC leaf positions. Positional errors from a normal distribution with means of 0·5, 1·0, 1·5 and 2·0 mm and a standard deviation of 0·1 mm were randomly applied to 50, 75 and 100% of 177 control points. In cases where the modified leaf position resulted in a possible leaf collision, the leaf pair separation was set to the smallest possible leaf gap of 0·5 mm. In all, 12 error plans representing the various errors introduced to the MLC positions were generated and measured for each original plan. For simplicity, considering as an example, a positional error with a mean of 1·0 mm applied on 50% of control points will be referred to as '1·0–50%'.

Sensitivity analysis

Three types of analyses were performed to study the sensitivity of the gamma index in detecting errors that were deliberately introduced in the MLC positions. For the first analysis, the measured plans (with and without error) were compared with the predicted original plan (referred to as 'PR-MS') which is the regular QA procedure. The second analysis was done comparing the predicted plans with the induced errors and their corresponding error-free original predicted plans (referred to as 'PR-PR'). This was done to access the capability of the EPID to detect errors using the change in %GP. The last set of analysis was performed comparing the measured plans with error to that without error (referred to as 'MS-MS'). For all three types of analysis (i.e., PR-PR, MS-MS and PR-MS), the reference dose distribution was from the original (error free) plan or measurement.

Results and Discussion

Retrospective analysis

Figures 1–3 show the means and standard deviations of the gamma passing rates of the original improved gamma analysis compared to analysis based on EPID images renormalised to the dose value at centre of the field. The results are summarised in Table 1. When comparing the unnormalised plans to plans that have been renormalised to the centre of the field, all categories show similar means that are statistically insignificant (paired t-test, $p > 0{\cdot}05$, $\alpha = 0{\cdot}05$) (Figures 1–3, Table 1). This differs from a previous study that we conducted with prostate cancer plans, where there was a significant difference in unnormalised and renormalised plans.[12] As a result, unnormalised improved gamma plans can be analysed to show accurate results. In terms of clinically relevant gamma passing rates, an average gamma passing rate of 98·3 is presented for 3%/3 mm and 93·7 is presented for 2%/2 mm.

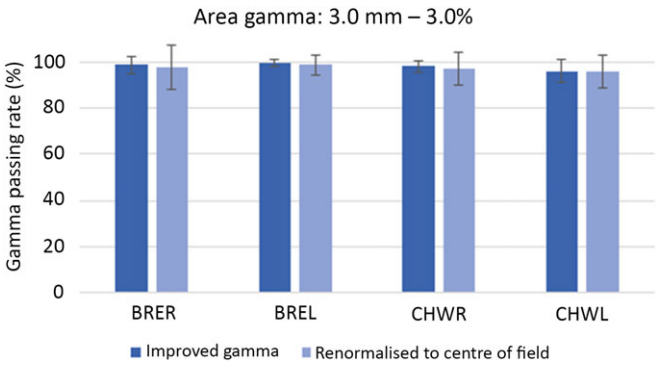

Figure 1. Bar chart of mean gamma passing rates for breast right (BRER) ($n = 50$), breast left (BREL) ($n = 50$), chest wall right (CHWR) ($n = 50$) and chest wall left (CHWL) ($n = 50$) treatment plans at 3% dose difference (DD) and 3 mm distance to agreement (DTA). The error bars represent the standard deviation of the corresponding values.

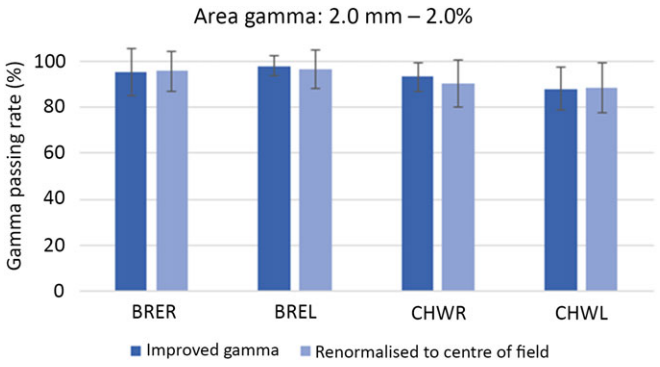

Figure 2. Bar chart of mean gamma passing rates for breast right (BRER) ($n = 50$), breast left (BREL) ($n = 50$), chest wall right (CHWR) ($n = 50$) and chest wall left (CHWL) ($n = 50$) treatment plans at 2% DD and 2 mm DTA. The error bars represent the standard deviation of the corresponding values.

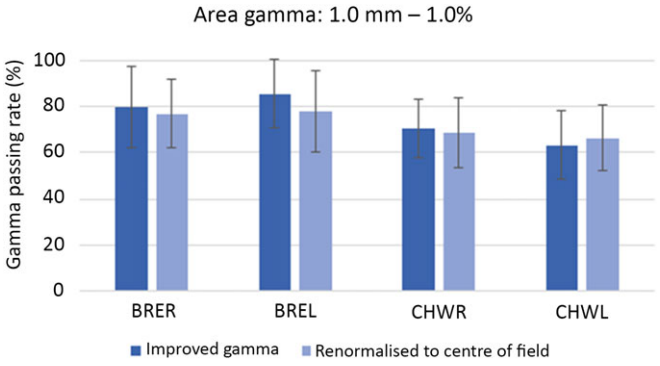

Figure 3. Bar chart of mean gamma passing rates for breast right (BRER) ($n = 50$), breast left (BREL) ($n = 50$), chest wall right (CHWR) ($n = 50$) and chest wall left (CHWL) ($n = 50$) treatment plans at 1% DD and 1 mm DTA. The error bars represent the standard deviation of the corresponding values.

Figures 4–6 show the means and standard deviations of the gamma passing rates of symmetric compared to asymmetric fields. The results are summarised in Table 2. When comparing the improved gamma plans of symmetric and asymmetric plans, all categories show mean differences that are statistically significant (t-test, $p < 0{\cdot}05$, $\alpha = 0{\cdot}05$) (Figures 4–6, Table 2). Symmetric plans contain fields that are symmetric on at least one axis. On the other

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Table 1. Mean gamma passing rates for breast right (BRER) ($n = 50$), breast left (BREL) ($n = 50$), chest wall right (CHWR) ($n = 50$) and chest wall left (CHWL) ($n = 50$) of improved gamma and normalised to the centre of the field treatment plans

	Improved gamma			Normalised to the centre of the field		
	3%/3 mm	2%/2 mm	1%/1 mm	3%/3 mm	2%/2 mm	1%/1 mm
BRER	98·8 ± 3·5	95·4 ± 10·3	79·6 ± 17·7	97·9 ± 9·5	95·7 ± 8·8	76·9 ± 15·0
BREL	99·6 ± 1·4	98·1 ± 4·5	85·7 ± 14·9	99·0 ± 4·4	96·8 ± 8·2	78·0 ± 17·5
CHWR	98·4 ± 2·5	93·4 ± 6·1	70·6 ± 12·6	97·1 ± 7·0	90·5 ± 10·4	68·6 ± 15·2
CHWL	96·2 ± 5·2	88·0 ± 9·4	63·4 ± 14·9	95·9 ± 6·9	88·4 ± 10·9	66·4 ± 14·4

Table 2. Mean gamma passing rates for breast symmetric ($n = 75$), breast asymmetric ($n = 25$), chest wall symmetric ($n = 18$) and chest wall asymmetric ($n = 82$) fields

	Symmetric			Asymmetric		
	3%/3 mm	2%/2 mm	1%/1 mm	3%/3 mm	2%/2 mm	1%/1 mm
BRE	99·9 ± 0·3	99·0 ± 3·0	87·2 ± 13·3	97·1 ± 4·8	90·1 ± 13·1	69·1 ± 18·3
CHW	99·5 ± 1·0	96·0 ± 7·2	77·8 ± 17·1	96·8 ± 4·4	89·6 ± 8·2	64·7 ± 12·4
All	99·8 ± 0·5	98·4 ± 4·3	85·4 ± 14·5	96·9 ± 4·5	89·7 ± 9·5	65·7 ± 14·1

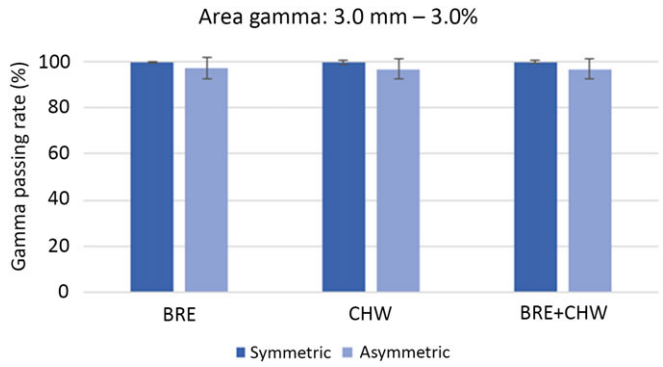

Figure 4. Bar chart of mean gamma passing rates for breast symmetric ($n = 75$), breast asymmetric ($n = 25$), chest wall symmetric ($n = 18$) and chest wall asymmetric ($n = 82$) treatment plans at 3% DD and 3 mm DTA.

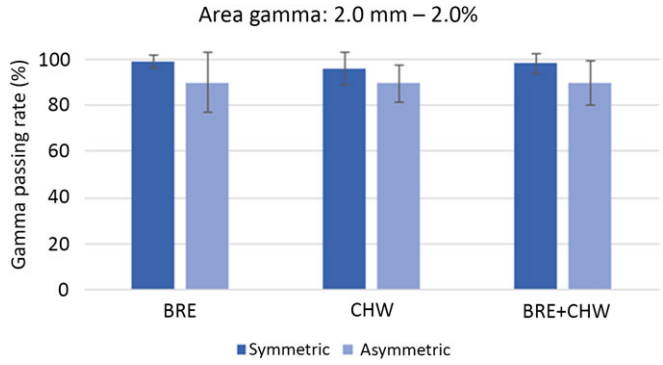

Figure 5. Bar chart of mean gamma passing rates for breast symmetric ($n = 75$), breast asymmetric ($n = 25$), chest wall symmetric ($n = 18$) and chest wall asymmetric ($n = 82$) treatment plans at 2% DD and 2 mm DTA.

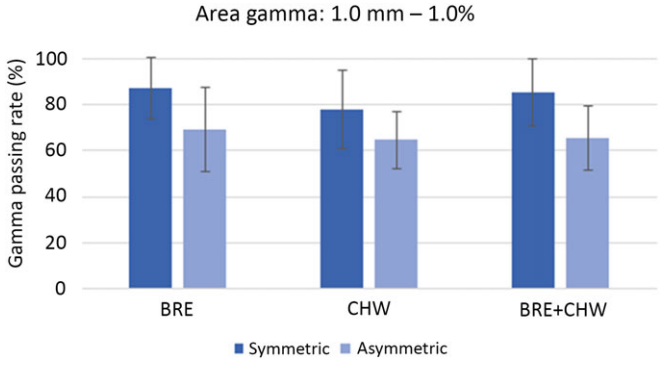

Figure 6. Bar chart of mean gamma passing rates for breast symmetric ($n = 75$), breast asymmetric ($n = 25$), chest wall symmetric ($n = 18$) and chest wall asymmetric ($n = 82$) treatment plans at 1% DD and 1 mm DTA.

hand, asymmetric plans contain fields with no symmetry on any axis. These are fields associated with the mono-isocentric technique used for simultaneous treatment of both the breast and supraclavicular nodes. The analysis shows that symmetric and asymmetric fields are in fact different in delivery and QA. In terms of clinically relevant gamma passing rates, an average gamma passing rate of 99·8 ± 0·5 is presented for 3%/3 mm symmetric plans and 96·9 ± 4·5 is presented for 3%/3 mm asymmetric plans. An average gamma passing rate of 98·4 ± 4·3 is presented for 2%/2 mm symmetric plans and 89·7 ± 9·5 is presented for 2%/2 mm asymmetric plans. Gamma analyses were performed comparing lateral and medial breast treatment plans. However, the results show no significant differences in area gamma, irrespective of the criteria used. The plans were also re-measured to confirm reproducibility of results.

Treatment fields for the asymmetric plans considered in this study comprised of field sizes ranging from a minimum field size of 119 cm^2 to a maximum field size of 316·8 cm^2. To help understand the effect of the field size, these were grouped into three: small, medium and large field sizes. The results show that the area gamma passing rate decreases in values with increasing field size. For small fields ranging from 119 to 184 cm^2 (n = 71), a 3%/3 mm gamma passing criteria shows an average gamma passing rate of 98·0 ± 3·0, and 91·4 ± 8·4 for 2%/2 mm. For medium fields ranging from 184·24 to 221·4 cm^2 ($n = 72$), a 3%/3 mm gamma passing criteria show an average gamma passing rate of 97·4 ± 2·6, and

https://doi.org/10.1017/S1460396920000072 Published online by Cambridge University Press

Table 3. Gamma passing values analysed for the comparison of the predicted plans with the induced errors and their corresponding error-free original predicted plans (PR-PR)

	BRER			BREL			CHWR		
Error	3%/3 mm	2%/2 mm	1%/1 mm	3%/3 mm	2%/2 mm	1%/1 mm	3%/3 mm	2%/2 mm	1%/1 mm
0·5 mm – 50%	100·0	100·0	99·4	100·0	100·0	99·4	100·0	100·0	97·6
0·5 mm – 75%	100·0	100·0	98·4	100·0	100·0	95·7	100·0	100·0	91·3
0·5 mm – 100%	100·0	99·9	93·6	100·0	100·0	82·2	100·0	97·4	79·2
1·0 mm – 50%	100·0	99·8	94·2	99·9	99·3	85·0	100·0	98·4	80·4
1·0 mm – 75%	99·8	99·2	75·9	100·0	97·5	68·7	98·6	91·6	70·3
1·0 mm – 100%	99·9	95·8	59·9	96·8	80·9	48·3	96·1	86·0	61·5
1·5 mm – 50%	100·0	98·9	74·4	99·9	94·5	60·0	98·8	89·8	62·4
1·5 mm – 75%	99·6	94·2	58·5	96·3	80·0	49·5	91·1	77·8	50·4
1·5 mm – 100%	98·8	87·8	55·9	89·2	69·8	41·2	84·5	70·0	47·9
2·0 mm – 50%	99·7	95·6	62·0	97·7	84·5	50·7	94·2	81·7	55·6
2·0 mm – 75%	98·2	81·2	46·9	88·3	70·6	39·1	79·6	65·4	41·4
2·0 mm – 100%	86·0	63·5	38·9	75·4	59·9	32·2	75·5	62·3	38·6

Table 4. Mean gamma passing values analysed for the comparison of the measured plans (with and without error) with the predicted original plan (PR-MS)

	BRER			BREL			CHWR		
Error	3%/3 mm	2%/2 mm	1%/1 mm	3%/3 mm	2%/2 mm	1%/1 mm	3%/3 mm	2%/2 mm	1%/1 mm
No error	99·9 ± 0·0	97·5 ± 0·4	62·3 ± 15·8	100·0 ± 0·0	100·0 ± 0·1	94·7 ± 0·7	99·9 ± 0·2	96·8 ± 0·7	75·0 ± 0·6
0·5 mm – 50%	99·9 ± 0·0	96·5 ± 0·8	63·2 ± 9·7	100·0 ± 0·0	99·6 ± 0·2	88·9 ± 2·0	99·7 ± 0·2	92·9 ± 1·1	69·1 ± 3·1
0·5 mm – 75%	99·9 ± 0·0	94·5 ± 3·8	58·9 ± 14·3	100·0 ± 0·0	99·4 ± 0·6	85·7 ± 5·0	99·6 ± 0·3	93·8 ± 1·9	69·5 ± 2·6
0·5 mm – 100%	99·7 ± 0·2	92·3 ± 2·3	56·3 ± 9·6	100·0 ± 0·1	99·2 ± 0·0	72·8 ± 6·9	97·0 ± 0·6	87·2 ± 2·3	62·4 ± 1·5
1·0 mm – 50%	99·4 ± 0·2	91·6 ± 1·6	56·5 ± 9·6	99·9 ± 0·1	98·1 ± 0·5	81·0 ± 2·3	97·9 ± 1·6	87·2 ± 3·2	57·8 ± 3·0
1·0 mm – 75%	99·2 ± 0·2	92·1 ± 0·7	59·3 ± 3·5	99·4 ± 0·5	91·2 ± 2·1	65·2 ± 3·2	94·7 ± 1·1	83·3 ± 1·6	56·5 ± 1·6
1·0 mm – 100%	93·1 ± 5·7	82·0 ± 6·8	50·1 ± 5·2	94·9 ± 3·0	79·3 ± 4·2	47·1 ± 3·0	89·4 ± 3·2	75·0 ± 0·9	47·0 ± 1·5
1·5 mm – 50%	97·7 ± 1·5	84·0 ± 7·4	49·5 ± 9·7	99·6 ± 0·1	91·8 ± 0·6	58·8 ± 1·6	93·6 ± 1·6	81·5 ± 2·5	53·2 ± 0·8
1·5 mm – 75%	93·8 ± 4·4	80·3 ± 8·2	48·3 ± 6·6	93·9 ± 3·6	79·2 ± 5·6	48·9 ± 2·4	84·6 ± 1·2	69·7 ± 2·2	40·9 ± 1·5
1·5 mm – 100%	91·9 ± 1·6	74·8 ± 2·9	41·0 ± 6·5	88·3 ± 2·0	68·0 ± 5·5	44·7 ± 10·3	78·3 ± 1·8	63·4 ± 2·8	37·7 ± 6·5
2·0 mm – 50%	94·7 ± 3·0	78·7 ± 6·7	45·5 ± 5·2	94·7 ± 2·2	80·7 ± 5·4	48·0 ± 6·6	89·1 ± 0·4	74·5 ± 1·5	45·1 ± 2·3
2·0 mm – 75%	89·8 ± 3·7	74·5 ± 2·2	44·0 ± 2·6	85·7 ± 3·9	68·3 ± 5·6	39·0 ± 5·0	74·2 ± 3·3	59·1 ± 4·4	32·6 ± 4·1
2·0 mm – 100%	78·2 ± 7·6	55·8 ± 8·6	29·4 ± 9·5	73·9 ± 3·7	59·1 ± 4·5	34·3 ± 3·7	70·4 ± 2·7	55·4 ± 2·8	30·7 ± 0·4

90·1 ± 6·3 for 2%/2 mm. For large fields ranging from 221·4 to 316·8 cm^2 (n = 71), a 3%/3 mm gamma passing criteria show an average gamma passing rate of 95·2 ± 6·4, and 87·6 ± 12·6 for 2%/2 mm. The lower passing rates for the larger fields can be attributed to such asymmetric fields being closer to the edge of the imager, where measured dose values are known to exhibit significant uncertainty than those predicted by the TPS.[13]

According to the recommendations of AAPM Task Group No. 218,[14] several institutions have suggested varied criteria for acceptable IMRT QA verification plans for various dosimetric tools. Palta et al.[15] suggest a confidence limit of 10% (2 mm DTA) and action level of 15% (3 mm DTA) for a high dose, high gradient region; a confidence limit of 3% and action level of 5% for the high dose, low gradient region, and a confidence limit of 4% and action level of 7% for the low dose, low gradient region. Using the suggestions of Palta et al.,[15] TG-119[16] proposed γ passing rates of 87·6% for film and 93% for arrays at 3%, 3 mm. Basran and Woo[17] recommended γ thresholds of 95% for non-head and neck cases and 88% for head and neck (HN) cases using criteria of 3%/3 mm. De Martin et al.[18] suggested a confidence limit of 95·3% at 4%/3 mm following their analysis of 57 HN IMRT plans. Bailey et al.[19] proposed a γ passing rates for prostate plans to be 80·4% at 2%/2 mm and 96·7% at 3%/3 mm for global normalisation and 66·3% at 2%/2 mm and 90·8% at 3%/3 mm for local normalisation. For HN plans, thresholds proposed were 77·9% at 2%/2 mm and 93·5% at 3%/3 mm for global normalisation and 50·5% at 2%/2 mm and 70·6% at 3%/3 mm for local normalisation.

As mentioned in the Introduction section, our institution evaluates breast IMRT plans with a γ passing rate of 95% at 3 mm, 3% using a global improved gamma criterion. Compared to values in

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Table 5. Mean gamma passing values analysed for the comparison of the measured plans with error to that without error (MS-MS)

	BRER			BREL			CHWR		
Error	3%/3 mm	2%/2 mm	1%/1 mm	3%/3 mm	2%/2 mm	1%/1 mm	3%/3 mm	2%/2 mm	1%/1 mm
0·5 mm – 50%	100·0 ± 0·0	100·0 ± 0·1	99·7 ± 0·3	100·0 ± 0·0	100·0 ± 0·1	99·5 ± 0·2	100·0 ± 0·0	100·0 ± 0·0	97·5 ± 1·2
0·5 mm – 75%	100 ± 0·0	100·0 ± 0·1	99·6 ± 0·2	100·0 ± 0·0	100·0 ± 0·0	96·5 ± 0·3	100·0 ± 0·0	100·0 ± 0·0	91·3 ± 3·1
0·5 mm – 100%	100·0 ± 0·1	100·0 ± 0·1	95·1 ± 1·0	100·0 ± 0·0	99·9 ± 0·2	87·0 ± 1·1	100·0 ± 0·0	96·8 ± 0·4	80·2 ± 0·5
1·0 mm – 50%	100·0 ± 0·0	99·8 ± 0·2	95·5 ± 0·5	99·9 ± 0·1	99·5 ± 0·4	86·7 ± 1·4	100·0 ± 0·0	98·2 ± 1·1	79·8 ± 8·6
1·0 mm – 75%	99·8 ± 0·2	99·3 ± 0·2	80·8 ± 6·4	100·0 ± 0·0	98·5 ± 0·2	73·0 ± 2·4	98·7 ± 1·1	91·9 ± 3·1	74·2 ± 4·8
1·0 mm – 100%	99·9 ± 0·2	97·3 ± 2·7	60·6 ± 4·6	97·4 ± 2·0	82·6 ± 2·6	51·7 ± 1·0	94·9 ± 2·0	84·6 ± 3·4	62·2 ± 3·5
1·5 mm – 50%	99·9 ± 0·0	98·9 ± 0·2	77·7 ± 5·6	99·7 ± 0·3	93·4 ± 0·8	63·8 ± 0·6	98·5 ± 0·2	89·3 ± 0·7	63·7 ± 4·6
1·5 mm – 75%	99·5 ± 0·2	94·9 ± 2·3	61·0 ± 10·2	96·7 ± 1·9	81·6 ± 6·3	53·0 ± 3·6	89·5 ± 1·0	77·5 ± 1·5	51·0 ± 1·7
1·5 mm – 100%	99·0 ± 0·2	87·7 ± 1·0	55·8 ± 3·8	89·1 ± 3·8	71·0 ± 2·1	44·4 ± 7·9	82·7 ± 2·8	68·1 ± 1·8	49·2 ± 2·4
2·0 mm – 50%	99·7 ± 0·1	95·3 ± 0·8	62·6 ± 4·3	97·5 ± 4·3	85·7 ± 5·8	55·1 ± 7·2	93·8 ± 0·2	81·4 ± 1·0	54·6 ± 3·0
2·0 mm – 75%	98·6 ± 0·1	81·4 ± 2·5	46·2 ± 3·1	88·5 ± 3·1	72·5 ± 4·0	39·4 ± 4·9	79·3 ± 3·1	64·5 ± 6·0	37·6 ± 6·3
2·0 mm – 100%	87·2 ± 6·0	65·9 ± 3·2	38·9 ± 0·9	76·1 ± 0·9	61·3 ± 4·4	33·2 ± 4·3	75·3 ± 2·5	60·7 ± 2·3	37·3 ± 1·1

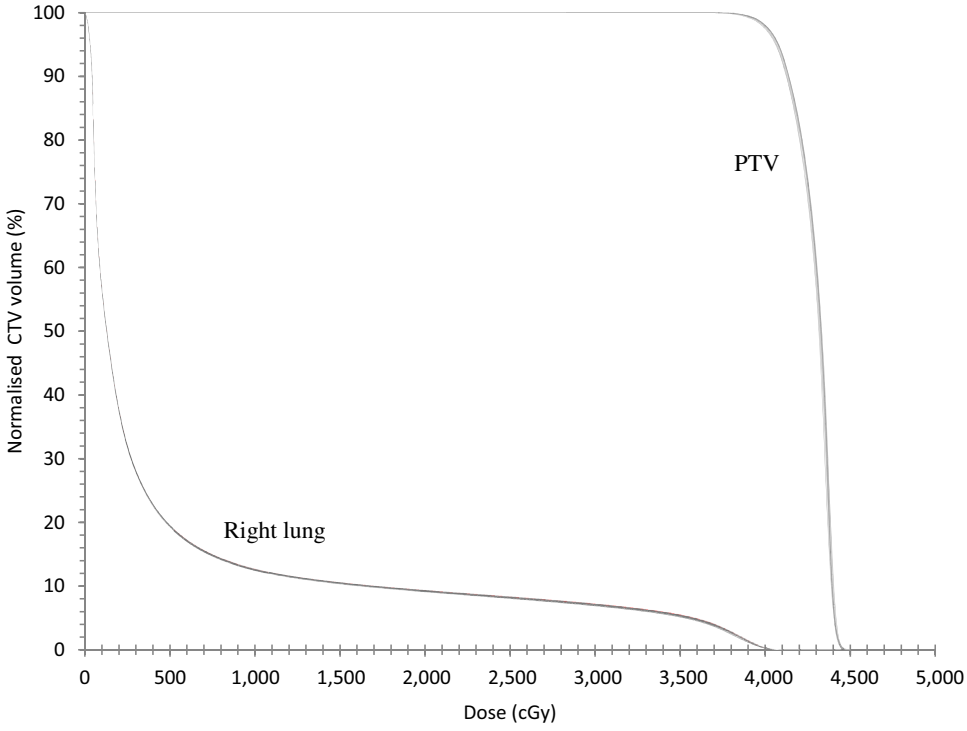

Figure 7. Dose volume histogram (DVH) of the clinical target volume (CTV) and organ at risk (OAR) (right lung) of the 13 error induced and the original (error free in red) breast right (BRER) treatment plans.

the literature, these passing rates are already stricter than the ones proposed by other institutions. Our study shows that not only is the EPID an effective tool for pre-treatment QA, but that even stricter gamma values can be achieved for breast IMRT plans using an EPID PD.

In this study, single gamma criterion was used to analyse the data. That is, a single threshold (e.g., γ passing rate of 95% at 3 mm, 3%) was used to analyse each portal image. Our results, however, reveal an enhanced sensitivity with the different criterions and as such we propose multigamma criteria to accommodate these enhancements in the sensitivity of the tool. That is, the use of more than one threshold (e.g., γ passing rate of 98% at 3 mm DTA, 3% DD and 94% at 2 mm DTA, 2% DD). With this approach, a stricter gamma passing rate (98%) is enforced with the less strict passing criterion (3 mm, 3%) in conjunction with a less strict gamma passing rate (94%) enforced on a stricter passing criterion (2 mm, 2%). The goal of these multigamma criteria is to reveal hidden errors from the less sensitive criteria with the stricter criteria. The use of 1 mm, 1% is not recommended due to the limitations of pixel resolution of the EPID (0·336 and 0·392 mm).

Sensitivity test

Tables 3–5 show the mean gamma values analysed for PR-PR, PR-MS and MS-MS plans. Figures 7–9 show the dose volume histogram (DVH) of the original and error-free BRER, BREL and CHWR plans. As shown in the DVHs of the error induced

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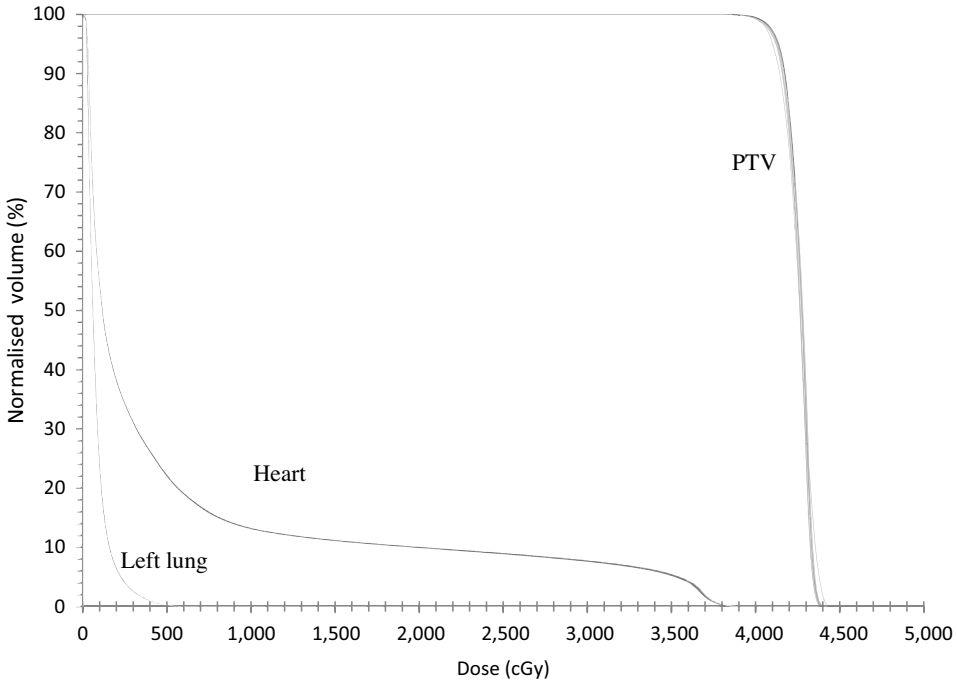

Figure 8. DVH of the CTV and OARs (left lung and heart) of 13 error induced and the original (error free in red) breast left (BREL) treatment plans.

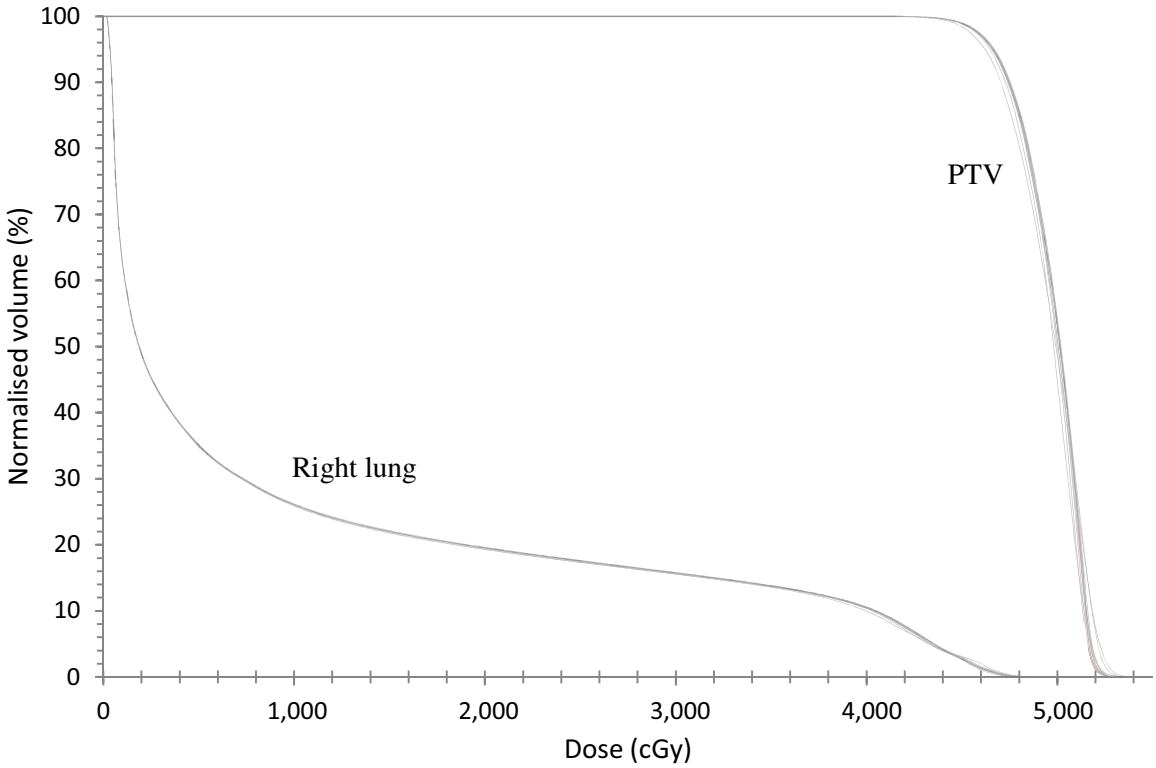

Figure 9. DVH of the CTV and OAR (right lung) of 13 error induced and the original (error free in red) asymmetric chest wall right (CHWR) treatment plans.

in symmetric (BRER and BREL) plans (Figures 7–8), there is minimal deviation in the shape of the histogram when comparing the error-free and error-induced plans. As the induced error is increased, the sensitivity of each gamma criterion is revealed. For example, the 3 mm, 3% criterion does not reveal errors until a 1 mm MLC error is induced; however, the 2 mm, 2% criterion will reveal smaller induced MLC errors (0·5 mm). Comparing the experimental MS-MS values with the theoretical PR-PR values, the results agree that sensitivity is consistent with both theoretical and experimental results. There is an increased but still non-significant deviation in the asymmetric (CHWR) plan (Figure 9). The results show that even with the largest error induced (2·0 mm, 100% of control points), the induced errors result in an insignificant change in dose that would be delivered to the patient irrespective of

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the treatment type or geometric shape of the field (symmetric or asymmetric). However, the gamma analyses (Tables 3–5) show that the EPID is sensitive enough to detect even the slightest change in MLC positioning error. Similarly to result from the retrospective analysis, the gamma passing rates decrease with stricter gamma criterion as well as the increase in error. These results from this study further support the implementation of multigamma criteria.

At our institution, plans are carefully optimised to ensure that, in addition to a conformal and homogeneous dose to the target, a minimal dose is delivered to all OARs. With even a 2·0 mm at 100% of control points error induced to the MLCs, the maximum DD less than 2% to the CTV was estimated to be less than 0·5% for the OARs. These values are below the 5% threshold value suggested by Mu et al.[20] in HN IMRT cases that would contribute to a dose delivery that could cause significant damage to the healthy tissue.

Conclusions

In this study, we have demonstrated that PD can be used effectively for patient-specific QA for breast IMRT plans. A stricter multigamma criteria approach with 3%/3 mm improved gamma criterion with a passing rate of 98% and a 2%/2 mm improved gamma criterion with a passing rate of 94% can be achieved without increased resources. In addition, the PD tool is sensitive enough to detect MLC positioning errors that contribute to even insignificant dose changes to the CTV and OAR.

Acknowledgements. None.

Financial Support. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Conflicts of Interest. None.

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