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The sensitivity of patient-specific IMRT QA methods in detecting systematic errors: field-by-field versus single-gantry-angle composite

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Abstract. This study evaluated the effect of small systematic errors, such as those from a multileaf collimator (MLC), on the quality of intensity modulated radiotherapy (IMRT) treatment plan delivery. Two IMRT quality assurance (QA) verification techniques, field-by-field (FBF) and single-gantry-angle composite (SGAC), were performed to evaluate both original and modified plans using a 2D ion chamber array detector. The dose distributions measured by the array detector for both FBF and SGAC were compared with the dose distribution calculated by the treatment planning system (TPS). FBF was found to be more sensitive than SGAC at detecting small systematic errors such as the opening and closing of the MLC's segments, which were evaluated with respect to a gamma-index of 3%/3 mm and 2%/2 mm. The systematic errors involved in closing the segments of the anterior field by 2 mm and 3 mm showed a significant difference compared with the original field (unmodified): $83.1 \pm 1.7\%$ and $42.9 \pm 1.9\%$ gamma-index passing rates, respectively, for FBF. For SGAC, the magnitude of closing the MLC by 2 mm remained unnoticed and resulted in a $95.1 \pm 2.61\%$ gamma-index passing rate. Opening the MLC by 2 mm gave a false negative, but more than 5% of the rectum received 75 Gy, which exceeded the tolerance radiation dose recommended by the Quantitative Analysis of Normal Tissue Effects in the Clinic (QUANTEC).

1. Introduction

Various QA methods have been developed to evaluate the accuracy of the IMRT technique. One of the most popular tools for performing patient-specific IMRT QA techniques is the 2D dosimetric comparison between the treatment plan and the measurement. This method can be divided into three types: field-by-field (FBF), single-gantry-angle composite (SGAC) and patient-gantry-angle composite (PGAC). After the measurement is obtained, a gamma analysis can be performed. The accepted gamma analysis criteria of a 3% dose difference and a 3-mm distance to agreement (DTA) are the most commonly used (TG 119)[1].

With SGAC, all treatment fields are delivered to a planar detector, such as a 2D array detector or an electronic portal imaging device, at a gantry angle zero, and the summation of these fields is evaluated and compared to the expected calculated dose by the treatment planning system on a phantom. For SGAC, this is a composite dose distribution, whereby all high-dose, steep gradient and low-dose regions are summed together. Thus, it may be difficult to detect errors that are being masked within the



composite dose distribution and/or to determine which treatment fields are causing the problem. However, FBF analysis allows for the evaluation of each field individually and therefore the detection of any individual field errors. Notably, the FBF technique also delivers the verification plan using a gantry angle of zero, and the measured dose is then compared to the calculated dose by the treatment planning system (TPS) on a phantom.

With a PGAC IMRT QA, the entire treatment plan is recalculated on the phantom's geometry and then delivered to the phantom as it would be to a patient, while considering the original plan's parameters, such as gantry and collimator angles [2]. When performing patient-specific IMRT QA, one drawback to this technique is a weak-to-moderate correlation between clinically relevant errors and 2D gamma analysis passing rates. Nelms et al. [3] introduced various errors in the IMRT treatment fields and found no relationship between the dose errors that were introduced and the 2D gamma analysis passing rates to anatomic regions of interest. Budgell et al. [4] concluded that when 2D gamma analysis is performed using a 3% dose difference and a 3-mm DTA, both result and error detectability are heavily dependent on the plane chosen for measurement acquisition, and no relationship could be discovered between the error levels in several verification planes.

Numerous investigators have evaluated the dosimetric effect of leaf positioning errors. For example, Luo et al. [5] evaluated the link between leaf position systematic errors and dosimetric impact in IMRT treatment for prostate patients. They deduced a linear relationship between the average MLC position error and the target [5] dose error, with a 1% planning target volume (PTV) dose difference, which was due to 0.2-mm systematic position errors of the leaves. Mu et al. [6] deliberately introduced random (± 1 mm and ± 2 mm) and systematic (± 0.5 mm or ± 1 mm) errors in the MLC positions for head and neck patients to evaluate the dosimetric effect. They found no significant dosimetric variation ($< 2\%$) for either PTV or OARs that were introduced by random leaf position errors up to 2 mm, while clinically significant differences (8% variation in D95% and approximately 12% in D0.1 cc to critical organs) were noticed by 1-mm systematic leaf position errors in complicated IMRT plans.

Consequently, the purpose of this project was to compare the sensitivity of FBF and SGAC with patient-specific IMRT QA methods in detecting small systematic errors in the treatment plan. Moreover, this project investigated the clinical significance of the different types of systematic errors that were introduced. The focus of this study was mainly on the PTV and the rectum, following the clinical guidance of ICRU 83 [7] on PTV and Quantitative Analysis of Normal Tissue Effects in the Clinic (QUANTEC) [8] dose constraints for OARs.

2. Materials and methods

2.1. Detector and setup

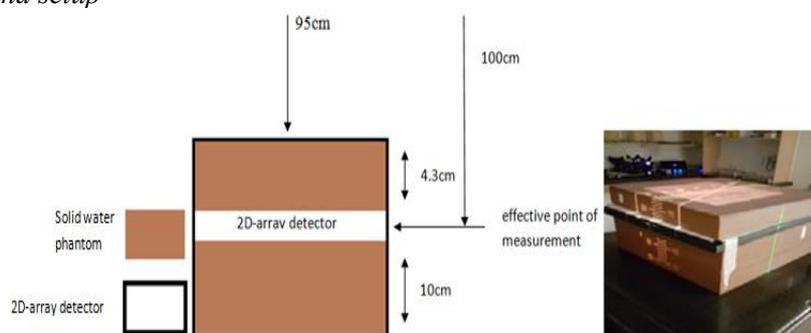


Figure 1. Experiment setup.

The radiation detector employed in this research was the OCTAVIUS detector Array Seven29™ (PTW, Freiburg, Germany). This device is a 2D detector array with 729 vented ionisation chambers that are arranged in a 27 cm \times 27 cm matrix. The ionisation chambers are equally spaced at 1 cm, centre to centre, and they cover an active area of 27 cm \times 27 cm. Each chamber has a size of 0.5 cm \times 0.5 cm \times 0.5 cm.

The reference point is located at 0.7 cm from the 2D array surface. The vented ionisation chambers are surrounded by PMMA. This device allows us to measure absorbed dose to water (Gy) and absorbed dose rate to water (Gy/min) while in a continuous operation mode [9]. The setup of the 2D array measurement that was used throughout this project is shown in figure 1; the measurement was performed using a solid brown phantom (water equivalent) for both the build-up and backscatter material. The total thickness of the build-up was 4.3 cm, and a 10-cm thickness was used as the backscatter.

2.2. Cross-calibration

A cross-calibration in the PTW software was performed before every measurement to account for any possible deviations in the output of the Linac. This was approached by creating a “calibration plan” in the treatment planning system with only one homogenous field size of 10 x 10 cm to deliver a dose of 1 Gy to the central chamber of the 2D-array detector. The radiation dose delivered to the central chamber was measured to be 0.978 Gy. Then, a calibration factor (K_{cross}) was determined using the following equation:

$$K_{\text{cross}} = \frac{D_{\text{TPS}}}{D_{\text{M}}} \quad (1)$$

D_{TPS} is the dose calculated by the treatment planning system, and D_{M} is the measured dose. This value was then used for correcting the remaining quality assurance verification measurements; the K_{cross} should be within 1.00 ± 0.03 .

2.3. Types of systematic errors

One prostate patient was selected for this study, the IMRT treatment plan of this patient was carried out using the SS technique with seven treatment fields. The IMRT prostate treatment plan was exported from the planning system as a Digital Imaging and Communications in Medicine (DICOM) file for further modifications. Then, a python code was created to enable modification to the treatment planning parameters. For this study, MLC leaf systematic errors were introduced by manipulating the IMRT plan's DICOM files by using the python code prior to delivery. This was done to analyse the effects of such errors on verification measurements. These altered DICOM files were exported back to the TPS system to simulate the effect of the errors on the patient treatment dose-volume histogram (DVH).

Both the original and the modified DICOM plans were then delivered to the 2D array. All measurements were performed on Siemens Oncor linear accelerators with 82 MLCs, and each leaf has a width of 10 mm. An IMRT patient-specific QA treatment plan verification was created in the Oncentra treatment planning (OTP) system. This was achieved by copying the treatment plan onto volumetric CTs of the distinct phantom/detector devices. The gantry and collimator angles were set at 0 degrees, and the predicted dose of the detector planes was calculated with a dose grid resolution of 5 mm. The verification plan was exported to the detector system (Verisoft), with the detector plane positioned at isocentre. Every verification field was exported to the accelerator console, and these were delivered and measured by the 2D array detector.

Two types of IMRT treatment verification were performed (FBF and SGAC) to evaluate the sensitivity of the IMRT QA verification techniques to detect errors that were created in the IMRT plan. The TPS-calculated individual and composite field dose distributions were transferred to Verisoft IMRT software for comparison. This software uses gamma analysis to make the comparison between the IMRT treatment plan on a phantom and the 2D array measured data.

2.4. DVH investigation

The clinical significance of the different types of introduced errors was investigated by importing the modified plans into the OTP system, and they also were evaluated via the Receiver Operating Characteristic (ROC) statistical test. These modified plans were recalculated using the original CT dataset. Hence, the resultant DVH can be compared directly with the DVH of the original IMRT plan. For this project, the comparison will focus on the PTV and the rectum as an important OAR for prostate IMRT treatment plans. Several authors have evaluated the relation between dose deviations in the DVHs

of IMRT treatment plans and the correlating evaluation of gamma-index-based QA measurements; they have concluded that the gamma-indexes are insufficiently sensitive to detect small systematic MLC errors, and there are clinically significant DVH differences for IMRT plans [10].

3. Results

The measured and calculated dose distribution patterns were imported to Verisoft IMRT software for analysis. For this study, the widely used gamma criteria of a 3% dose difference and 3-mm DTA were chosen, which are the accepted criteria of Galway University Hospital (GUH). Notably, a 3% local dose difference is more stringent than using the maximum dose in the entire field (global dose differences). For these analyses, gamma values were only derived in the area where the dose was higher than 10% of the maximum dose to exclude low-dose areas outside the treatment field.

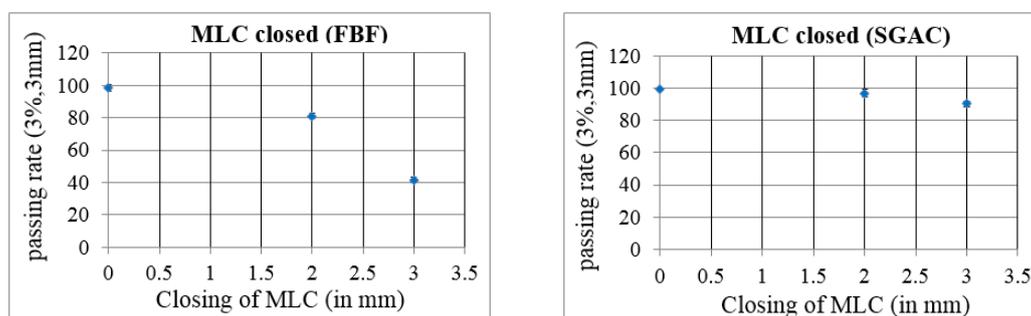


Figure 2. Average passing rates in relation to the introduced MLC closed error for FBF (LT image) and SGAC (RT image). The first reading point at 0 mm indicates the unmodified plan, followed by 2 mm and 3 mm.

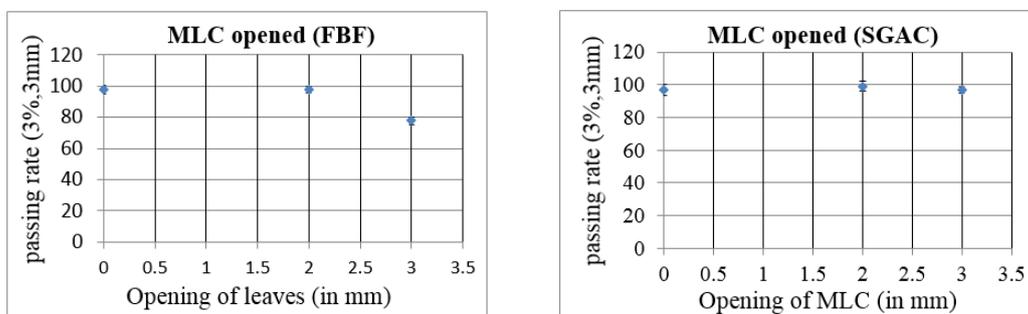


Figure 3. Average passing rates in relation to the introduced MLC opened error for FBF (LT images) and SGAC (RT image). The first reading point at 0 mm indicates the unmodified plan, followed by 2 mm and 3 mm.

Table 1. Evaluation of DVHs and ROC statistical tests regarding introduced errors.

Clinical guidance ICRU 83 & QUANTEC	MLC closed 2 mm	MLC closed 3 mm	MLC opened 2 mm	MLC opened 3 mm
PTV ($V_{95} \geq 95\%$)	72.31	71.96	73.64	73.98
Rectum ($V_{50} \leq 50\%$)	41.94	41.75	43.01	43.43
Rectum ($V_{60} \leq 40\%$)	32.24	31.98	33.36	33.69
Rectum ($V_{70} \leq 30\%$)	19.20	18.65	20.95	21.41
Rectum ($V_{75} \leq 5\%$)	1.95	1.38	6.19	7.96
ROC test	TP	TP	FN	TP

Table 2. Comparison of FBF and SGAC results with gamma-index criteria of 2%/2 mm and 3%/3 mm.

		FBF		SGAC	
		2%/2 mm (%)	3%/3 mm (%)	2%/2 mm (%)	3%/3 mm (%)
MLC closed	Original	95.5	98.5	98.8	98.8
	2 mm	41.5	83.1	72	95.1
	3 mm	17.5	42.9	64.6	91.5
MLC open	Original	95.5	98.5	98.8	98.8
	2 mm	85.3	97.65	94	100
	3 mm	47.8	78.1	95	100

4. Discussion

The patient-specific IMRT prostate plan was analysed by comparing measured and calculated dose distributions for both the FBF and the SGAC techniques. In general, the gamma passing rates were higher for SGAC compared to the FBF for both the original and the modified plans using both 3%/3 mm and 2%/2 mm gamma-index criteria. The magnitude of error detection varied depending on the type of error introduced and the IMRT QA verification method used. The results of adding a systematic error by closing the MLC on the gamma-index passing rate using FBF and SGAC are presented in figure 2. It was observed that the FBF method is more sensitive in detecting MLC errors than SGAC is. For instance, the smallest type of modification (2 mm) showed a significant difference in comparison with the original field (unmodified) and resulted in $83.1 \pm 1.7\%$ gamma-index passing rates, per the FBF; hence, the gamma-index failed. However, for SGAC, the magnitude of closing the MLC by 2 mm remains unnoticed and results in $95.1 \pm 2.61\%$ gamma-index passing rates, which result in a false negative test. Therefore, the method of choice for patient-specific IMRT QAs at GUH is FBF.

The clinical impact of all errors introduced in this study was evaluated and discussed with the oncologists in our department; this was achieved by assessing the DVH for both the PTV and the rectum. Importantly, several radiotherapy centres have considered a change in the mean PTV dose in prostate IMRT cancer cases, which is considered clinically significant. This value was proposed by Oliver [11]. However, in the GUH radiotherapy department, the oncologists are usually evaluating the plan to fulfil the recommendation of the ICRU83, which states that the PTV should have a minimum coverage of 95% and no more than 107% of the prescribed dose, considering the tolerance dose of the OARs.

Although opening the MLC segments by 2 mm passed the gamma-index criteria (3%/3 mm), the ROC statistical test showed a false negative. In addition, it had a significant clinical impact because 6.17% of the rectum received 75Gy; thus, it did not meet the minimum recommendations of ICRU 83 [7]. Only two modified plans (MLC closed by 2 and 3 mm) have met the clinical guidance (ICRU 83) [7] and subsequently been accepted by the radiation oncologists at GUH. However, the remaining modified plans did not satisfy the minimum requirement of the ICRU 83 (see table 1), particularly in exceeding the dose tolerance limits of the rectum ($V75 \leq 5\%$). FBF measurement is a time-consuming process; it would be faster to use SGAC. However, even when a stricter 2%/2 mm gamma analysis was used, SGAC remained insensitive to most types of introduced errors (see table 2).

It is evident that FBF is safer to use than SGAC. The QA methods used in this study were not only insensitive to certain error types but also time-consuming. This may raise the issue of reviewing IMRT procedures to detect large machine calibration errors, even though the primary aim of an IMRT QA is to detect errors that are specific to an individual patient's plan. Recently, log files have been developed on various treatment machines to address issues with conventional QA methods in detecting both small systematic and random errors. One of the advantages of using this method is that the log file can be obtained each time the plan is delivered. Therefore, it can be used during patient treatment. Log files

also offer a quick performance of IMRT plan checks and reduce the hours used in conventional QA methods to a few minutes. However, there are still concerns about whether the log file-based QA approach offers the same confidence as measurements that use one of the conventional QA methods, such as the one that was used in this project.

5. Conclusion

Both the original and the modified plans were analysed by comparing measured and calculated dose distributions via the FBF and SGAC IMRT QA techniques. Although the sensitivity of a particular method in detecting errors varied, depending on the types of introduced errors, FBF analysis proved more sensitive in detecting modified plans than SGAC did for both the gamma-index criteria of 3%/3 mm and 2%/2 mm. Future work could look at a composite analysis on the PTW array within the Octavius phantom, which would allow the IMRT QA to be measured at the appropriate gantry angle. Future work could also apply the techniques and methods that were used for the prostate in this study to the head and neck. This is because of increased modulation and irregular field shapes in the head and neck treatment plan due to the various overlapping structures, such as the brain stem and the optic tract.

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