Evaluation of the ability of a 2D ionisation chamber array and an EPID to detect systematic delivery errors in IMRT plans

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Abstract. Two clinical intensity modulated radiotherapy plans were selected. Eleven plan variations were created with systematic errors introduced: Multi-Leaf Collimator (MLC) positional errors with all leaf pairs shifted in the same or the opposite direction, and collimator rotation offsets. Plans were measured using an Electronic Portal Imaging Device (EPID) and an ionisation chamber array. The plans were evaluated using gamma analysis with different criteria. The gamma pass rates remained around 95% or higher for most cases with MLC positional errors of 1 mm and 2 mm with 3%/3mm criteria. The ability of both devices to detect delivery errors was similar.

1. Introduction

Intensity modulated radiotherapy (IMRT) utilises complex motion of the Multi-Leaf Collimator (MLC) to achieve highly conformal dose distributions. The position and movement of the leaves as well as other delivery parameters are susceptible to errors in IMRT delivery [1] so pre-treatment patient quality assurance (QA) is recommended. This QA is commonly performed with 2D or 3D dosimeters and the gamma evaluation technique which combines both dose difference and distance to agreement criteria and has become the current standard to provide a quantitative comparison [2]. However, there is limited evidence in the literature about the ability of such dosimeter systems to detect errors in IMRT. For example, pass rates of ArcCHECK measurements made with deliberately introduced systematic gap width errors of up to 2 mm were reported to be similar to error-free plans, using a 3%/3mm or 3%/2mm gamma criteria [3], whilst the MapCHECK device was reported to be more sensitive to MLC positioning errors than radiochromic film [4].

Recent recommendations indicate that each department should investigate the ability of their QA processes to detect errors [5]. The aim of this work was to investigate the ability of an EPID and a 2D ionisation chamber array to detect systematic MLC leaf position and collimator errors. A number of hypotheses were proposed to allow the evaluation of gamma pass rate results. The first hypothesis was that the detector systems can detect the smallest clinically significant error. For this to be true the gamma analysis pass rate will reduce by a statistically significant value when these errors are

introduced. Secondly, that the sensitivity to errors varies between detector systems. For this to be true the slope describing the reduction in pass rate with introduced error will be steeper for one of the detector systems. Thirdly, that a detector system becomes more sensitive to errors when the gamma tolerances are tightened. For this to be true the slope describing the reduction in pass rate with error will be steeper when tighter gamma criteria are used for the analysis.

2. Methods

Two clinical step-and-shoot IMRT plans, one prostate (PR) and one head and neck (H&N) plan, were selected. Both plans utilised 7 fields, with an average number of segments per field of 7.1 and 13.7 for the PR and H&N plans respectively. The plans were created using the Pinnacle[3] treatment planning system (TPS), V 9.0 (Philips Healthcare, USA) and calculated with a grid size of 0.25 cm³. An in-house computer programme written in Python was used to introduce errors to all segments for each field for both plans. Two MLC position errors were introduced. The first of these shifted all leaf pairs in opposite directions with offsets of 1, 2, and 3 mm applied, resulting in a larger leaf gap.The second error introduced shifted all leaf pairs with offsets of 1, 2, 3, and 4 mm in the same direction, resulting in the field aperture remaining the same size but being shifted in the X direction.

The plans were copied and modified in the MOSAIQ record and verify system, V2.30.04D1 (Elekta Ltd, UK), to allow field by field measurements with the gantry angle set to zero degrees. Collimator errors were also introduced with the initial collimator angle position of all beams increased by 1°, 2°, 3° and 5° respectively in the clockwise direction by manually editing the plan in the record and verify system. The original and edited plans were delivered using a Synergy linear accelerator (linac) (Elekta Ltd, UK). The delivered dose was measured with the EPID attached to the linac and a 2D ionisation array, MatriXX Evolution used with OmniPro-I'mRT V1.4.0.1 (IBA Dosimetry, Germany).

The measured dose for each field was compared to the calculated dose for the 'no-error' plan, using gamma analysis with 3%/3mm, 3%/2mm, and 2%/2mm criteria with a 10% threshold using OmniPro-I'mRT. It is assumed that the no-error plan was delivered without any errors. To allow import into OmniPro-I'mRT, the EPID images were converted to dose via a pixel calibration factor, which links the measured pixel value (under reference EPID conditions) of each element detector to the dose in water (under reference IMRT QA conditions). This correction was applied using an in-house program written in Matlab (Version 7.11.0.584 R20106). A renormalisation was applied to both calculated and measured (EPID, MatriXX) dose distribution to allow a global percentage difference (relative to the maximum dose in the field) to be used in the gamma analysis. The maximum dose value of the TPS calculated dose distribution was determined and then the inverse of this value was applied to result in a situation where 100% value was equivalent to the maximum dose in the TPS dose distribution. The renormalisation value applied to the TPS dose distribution was then applied to the measured dose distribution. A correction for the linac output factor at the time of measurement was applied to the measured data if its value was greater than 1%. The grid size of the raw MatriXX data was also converted to match that of the TPS calculated data using a cubic spline interpolation, due to its inherent resolution of 7.6 mm. OmniPro-I'mRT provides ability to shift the measured and planned dose distributions relative to each other prior to the analysis. This feature may be used to correct for setup errors or uncertainties. For the purpose of reproducibility this facility was not utilised in the methodology of the current study. The assumption was made that the detector was in all cases aligned correctly so the central pixel of the image created from the measurement was aligned automatically with the central pixel of the image created from the planning system when the data was imported into OmniPro-I'mRT.

To evaluate the first hypothesis, a Z-test was used to determine if for the given detector, a different pass rate was observed between the no-error plan and a plan with the smallest clinically significant error introduced. The smallest clinically significant error was defined as 1 mm for MLC position and 2° for collimator rotation, as errors of this magnitude are reported in the literature to have a clinically significant impact on IMRT plans [6, 7]. The p-value represents the probability that the null

hypothesis is correct. If a resulting value was less than 0.05, then there is a difference between the pass rate for the no-error plan and the pass rate for the plans with errors introduced. For the second and third hypotheses, a multiple linear regression test was used to compare the sensitivity of each detector for a given error type and plan. Detector, error size (magnitudes of error type) and the interaction between detector and error size were used as variables in each of the multiple linear regression models. Also, the 0.05 p-value was used to represent if the null hypothesis is correct. If a resulting value was less than 0.05, then the slopes of the gamma pass rate vs error size between the detectors were considered to be different.

   To determine the magnitude of the uncertainty, the prostate plan was measured three times for each detector on the same day to assess the short term reproducibility, and the plan was delivered on three different following weeks to evaluate the longer term reproducibility. The short and longer term reproducibility values were then combined [8].

3. Results

For the no-error plans, the gamma pass rates were 99.3% and 94.4% for the prostate plan and 91.9% and 93.3% for the H&N plan using EPI and MatriXX respectively. The results for the no-error plan and for the plans with MLC position and collimator rotation errors introduced are presented in Figure 1 and Figure 2. In order to allow comparison between detectors, the plotted values represent the average pass rate of all the fields in the plan. The error bars represent the one standard deviation, uncertainty values, for each device, which were ±0.67 and ±1.33 for EPID and MatriXX respectively. Pass rates were expected to reduce as the magnitude of the errors increased. However, pass rates increased when 1mm and 2 mm MLC position errors were introduced.

   The expected trend of pass rates reducing with increasing errors was seen with the collimator errors for both plans, e.g. the pass rate dropped from 90.7% to 68.6% when errors were introduced of 1° and 5° in the head and neck plan using the EPID for measurement. Similarly, the pass rate using the MatriXX reduced from 91.2% to 62.5%.
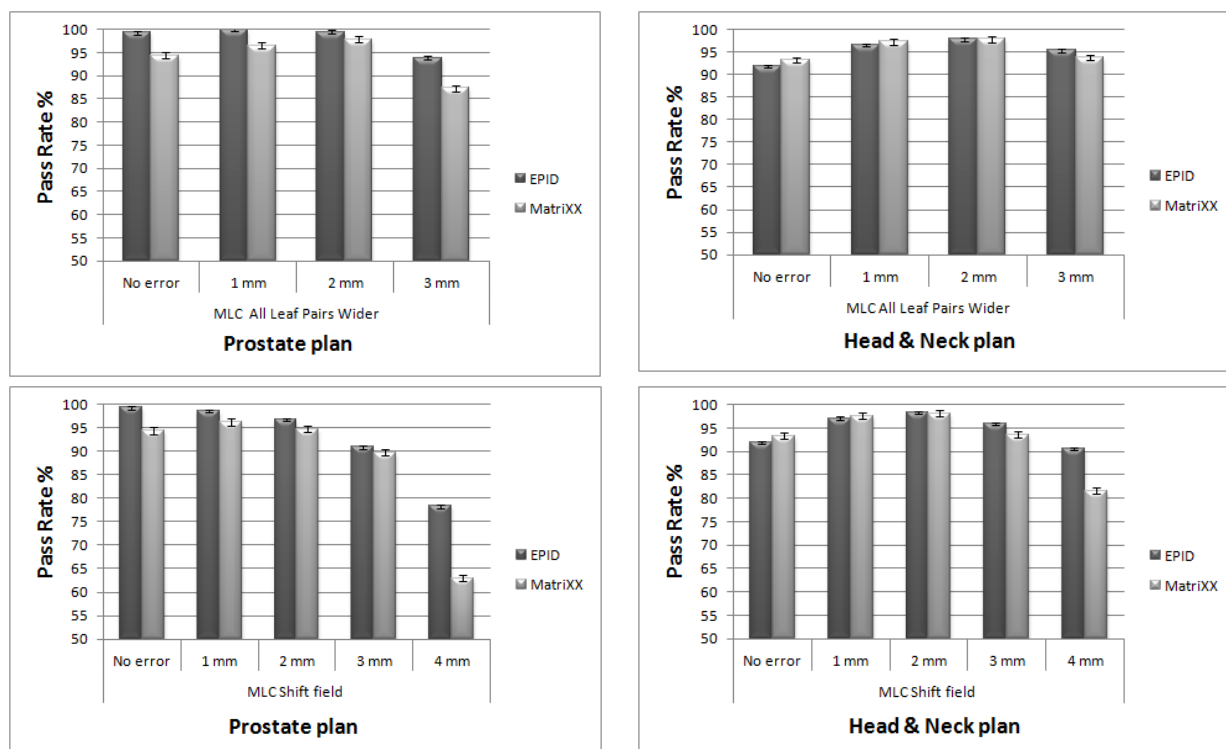

Figure 1: The gamma analysis pass rate measured using EPID and MatriXX detectors with 3%/3 mm criteria for prostate and head and neck IMRT plans without errors and with introduced MLC position errors.
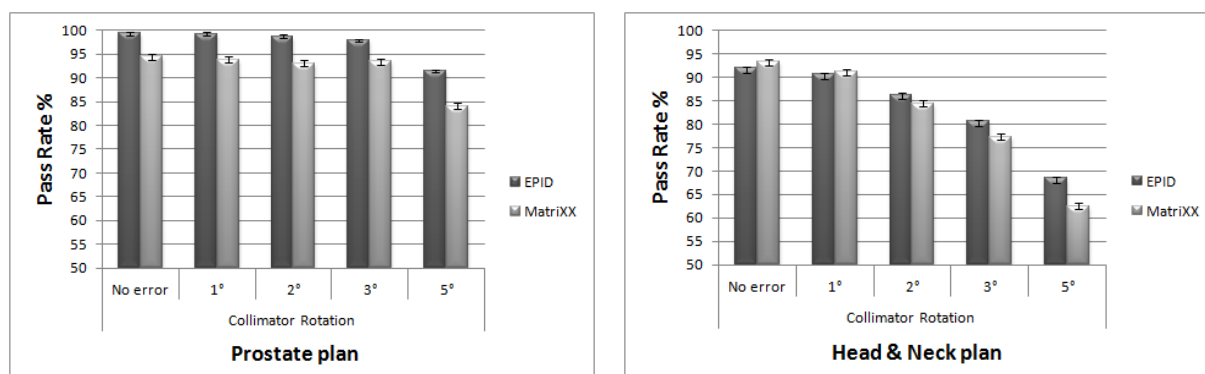
Figure 2: The gamma analysis pass rate measured using EPID and MatriXX detectors with a 3%/3mm criteria for prostate and head and neck IMRT plans without errors and with introduced collimator rotation errors.

The results for the first hypothesis are presented in Table 1. These results indicate that both detector systems had a similar lack of ability to detect the smallest clinically significant errors. Neither detector system considered was able to detect 1 mm MLC position errors or a 2° collimator error for the prostate plan. However, both detector systems were able to detect the 2° collimator error for the H&N plan.

The results for the second hypothesis are presented in Table 2. All of the comparisons produced a value greater than 0.05 which indicates that both detector systems (using the 3%/3mm gamma evaluation criteria) had a similar sensitivity for each plan and all error types with the exception of the collimator rotation errors in the H&N plan, in this instance the MatriXX was more sensitive for this type of error compared to the EPID.

The results for the third hypothesis are presented in Table 3. All of the results produced a value greater than 0.05, indicating that the rate of reduction in pass rates with increasing error magnitude did not change when the gamma criteria was tightened, i.e. the slopes were similar.

Table 1: The p-values from the Z-test to evaluate the ability of detector systems to detect the smallest clinically significant errors (1 mm or 2°) introduced, using 3%/3mm gamma evaluation criteria.

Plan	Error Type	EPID	MatriXX
PR	MLC all leaf pairs wider	0.822	0.938
PR	MLC shift field	0.158	0.916
PR	Collimator rotation	0.201	0.156
H&N	MLC all leaf pairs wider	1.000	0.998
H&N	MLC shift field	1.000	0.999
H&N	Collimator rotation	0.000	0.000

Table 2: The p-values from the linear regression test to evaluate the significance of differences between the detector systems (EPID-MatriXX), using 3%/3mm gamma evaluation criteria.

Plan	MLC all leaf pairs wider	MLC shift field	Collimator rotation
PR	0.878	0.307	0.699
H&N	0.723	0.350	0.005

Table 3: The p-values from the linear regression test to evaluate the significance of the difference between different gamma criteria for a given detector.

Plan	EPID			MatriXX		
	MLC all leaf pairs wider	MLC shift field	Collimator rotation	MLC all leaf pairs wider	MLC shift field	Collimator rotation
PR	0.869	0.286	0.442	0.938	0.937	0.830
H&N	0.356	0.756	0.306	0.878	0.232	0.757

4. Discussion

In general, the pass rates were higher for the prostate plan compared to the head and neck plan. This was attributed to the increased modulation and irregular field shapes in the head and neck plan. In addition, due to the large field sizes in the head and neck plan, for some fields part of the beam extended outside the detector area, resulting in missing data. In cases where the introduced MLC shift moved the delivered field further away from the detector area, a reduction in gamma pass rates would be expected. However, the magnitude of the effect of the missing data on the gamma analysis pass rates was not investigated in this study. Based on these results, the choice of acceptable pass rate may need to be reduced to less than 95% for complex plans. Although it was assumed for the purpose of this study that the (no-error) plans were delivered accurately in reality all measurements were subject to delivery uncertainties. To assess the increased pass rate when small MLC position errors were introduced, the monthly QA results were reviewed. The MLC position accuracy was found to be within the 1 mm tolerance, however, the field size was around 0.5 mm smaller than expected for each MLC bank. This may have contributed to the increased pass rates observed when a 1 mm error was introduced, however does not explain the pass rate increases when a 2 mm error was introduced. Further investigation to identify the cause of this result is planned. For the collimator rotation errors, the prostate plan was less sensitive than the head and neck plan, which was attributed to the relatively small field sizes used for the prostate plan while the head and neck plan has elongated fields.

The results indicate that none of the detector systems have the ability to consistently detect a 1 mm MLC position error when using the gamma analysis method. A 3%/3mm gamma criteria as presented here for hypothesis 1 and 2 is large when aiming to detect a 1 mm MLC position error. However, the analysis comparing tighter gamma criteria (from 3%/3mm to 3%/2mm to 2%/2mm) demonstrated reduced pass rates (for error-introduced, but also for no-error plan deliveries), but no significant differences in the change in pass rate with increasing error magnitude. Considering that the tightest gamma criteria used was 2%/2mm it was not expected that a 1 mm error would be identified. It may be possible to identify 1 mm errors using alternative methods such as leaf end detection or pixel intensity deviation or by using a tighter distance to agreement criterion in the gamma analysis.

5. Conclusion

Neither the EPID nor the 2D ion chamber array investigated in this study when utilised with a gamma analysis criteria between 2%/2mm and 3%/3mm were able to detect clinically significant MLC position errors of 1 mm, whereas both were able to detect 2° rotation errors for a head and neck plan. The sensitivity of both devices was similar in most cases investigated. Moreover, no significant improvement in the ability of the devices to detect errors was observed when changing gamma criteria as the pass rates reduced in a consistent manner for no-error and for error-introduced plan deliveries as the criteria became tighter. This preliminary work has highlighted the need to establish detector systems and assessment criteria that can detect clinically significant errors as well as the need to adapt QA systems based on particular treatment plan types.

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