Quantitative metrics for assessing IMRT plan conformity: A virtual phantom study

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Abstract. Intensity Modulated Radiation Therapy (IMRT) is a complex form of radiation delivery for the treatment of malignant tumours and other diseases. In IMRT treatment planning, quantitative assessment is crucial to measure and improve the plan quality and treatment delivery. The search for simple and universal quantitative metrics to assess IMRT treatment plan quality has been identified as important, but as yet not entirely successful. The aim of this study was to assess the IMRT treatment plan quality from the perspective of planning conformity. Conformity index (CI) was adopted to quantify the plan conformity. Virtual phantoms were developed for the initial conformity assessment, in order to form a basis for treatment plan inter-comparisons amongst the different IMRT techniques. A series of multi organs at risk (OARs) phantoms was developed to simulate the planning target volume (PTV) and OARs for different configurations. Conformity assessments were undertaken on all the IMRT plans generated using the virtual phantoms. This study has demonstrated the successful development of virtual phantoms to assess objectively and systematically the IMRT treatment plan conformity.

1. Introduction
IMRT planning is a complex and time-consuming process involving many parameters that impact on plan quality, treatment planning time, and delivery time. For IMRT treatment planning, the dose distributions tend to be more complex and highly heterogeneous because of the modulated fluence in each beamlet of every beam [1]. It has been found that excessive complexity in IMRT plans increase the dose uncertainty, prolongs the treatment time, and increases the susceptibility to changes in patient or target geometry [2]. Therefore, there is a need to improve the delivery efficiency while maintaining the plan quality.

To assure the IMRT plan quality, it is essential that there are adequate tools to quantify and compare the quality of different plans. The quality of IMRT treatment plans may be evaluated by developing testing tests or phantoms. These tests or phantom should be available for use and validation by radiotherapy centres using different commercially available treatment planning system.
(TPS). For this to take place, there was a need for standard and complex plans to be generated using a standard set of volumes, which were both clinically relevant and geometrically straightforward.

This work was carried out for the first time to develop a series of virtual phantom to assess the IMRT planning conformity. These phantoms were geometrically simple and simulated patient IMRT plans. They were then used to create patient plans utilising different IMRT techniques. The planning constraints were those commonly practised in the daily planning procedures. Later, the conformity index (CI) was used to examine and compare the conformity of the plans.

2. Methods

2.1. Development of virtual multi OARs phantoms

In this study, a series of virtual phantoms were designed to mimic a real patient IMRT treatment plans in a general way including the PTV and a number of adjacent OARs, where the location and dimension offer the possibility to simulate a tumour and the adjacent OARs. The PTV and OARs were positioned to simulate a range of different treatment sites where the IMRT technique is commonly used for example, at sites in the head and neck, pelvis and prostate. The rationale to have OARs at different distances from PTV was to simulate real clinical cases where the PTV might be located adjacent or overlap with OAR.

In the design of a phantom for characterising IMRT planning and delivery systems, Hunt et al. [3] proposed that the phantoms containing structures such as cones and deformed cylinders with variable orientation relative to anatomic axes were most suitable for plan assessment. With the aim of mimicking an IMRT treatment plan, the virtual phantoms were designed simulating a cylindrical-shaped PTV surrounded by two cylindrical shaped OARs, where the OARs were placed within close proximity to the PTV.

The separation of PTV-OARs was designed to have variable distances. This was intended to demonstrate the effect of dose conformity to PTV when the OAR moves closer to PTV. The selected planned distances were 30 mm, 20 mm, 10 mm and no separation. It was anticipated that the demands on the optimisation system becomes greater and makes it harder to achieve tight dose conformity to the PTV when distances between the structures decrease.

By using MATLAB® software (MathWorks, Natick, MA, United States) each phantom was designed to consist of a cylindrical-shaped PTV (diameter of 30 mm) and surrounded by two cylindrical-shaped OARs (each OAR is having the diameter of 20 mm). The planned PTV-OAR separation was 30 mm, 20 mm, 10 mm and no separation. For OAR, five locations were identified and they were consistently spaced at 45° interval. Location-1, Location-2, Location-3, Location-4 and Location-5 referred to the different location of OAR in each phantom. A schematic diagram of the virtual phantom is illustrated in Figure 1.

All the CT images of each phantom with complete target and organ structure information were preloaded into Oncentra MasterPlan® version 4.3 (Elekta Instrument AB, Stockholm, Sweden) and Tomotherapy® Planning Station , TomoH™ version 5.0.4.2 (Accuray Incorporated, Sunnyvale, CA, United States) for planning purposes.
2.2. IMRT planning

Three different IMRT techniques were investigated: step-and-shoot IMRT (SSIMRT), volumetric modulated arc therapy (VMAT) and helical tomotherapy (HT). These techniques were being used for patient treatment at Nottingham Radiotherapy Centre, Nottingham City Hospital Campus, Nottingham University Hospitals NHS Trust. In IMRT treatment planning, the priority (or penalty) settings in the optimisation process for all three techniques differ owing to the different optimisation algorithms employed. The SSIMRT plans were generated using 7 fields SSIMRT technique at gantry angles 0°, 56°, 103°, 154°, 206°, 257° and 304°. The VMAT plan was generated using the Oncentra Optimiser for an Elekta Synergy linear accelerator using 6 MV photons.

In these studies, the prescription dose to the PTV was for a total of 65 Gy, with 2.2 Gy per fraction. The protocol stipulated that not less than 95% of the PTV should receive at least 90% of the prescribed dose (58.5 Gy). The maximum PTV dose was that not more than 2% of the PTV should receive more than 110% of the prescribed dose (71.5 Gy). For OAR, dose constraint was designed to limit the maximum dose to be less than 40 Gy.

2.3. Evaluation tool

The treatment plans were evaluated using Dose Volume Histograms (DVH) generated by TPS. The dosimetric results were analysed for PTV and OARs. For PTV, the parameters $D_{2\%}$ and $D_{95\%}$ were used as surrogate markers for maximum and minimum doses. The volume of both the OARs that received doses of 40 Gy and 65 Gy ($V_{40Gy}$ and $V_{65Gy}$) were detailed in the respective treatment plans.

For the conformity analysis, the dose conformity was addressed by the metric of conformity index (CI) as recommended by ICRU Report 83 [4]. This index has been used for the evaluation and comparison of treatment plans and has become the ratio frequently implied when the term conformity index is used. CI is the ratio of reference isodose volume ($V_{RI}$) to target volume (TV) and calculated by using Equation (1). In these studies, the CI was calculated at reference isodose of 90% prescribed dose.

$$CI = \frac{V_{RI}}{TV}$$

2.4. Statistical analysis

To appraise the statistical differences in the parameters obtained between the IMRT techniques, simple descriptive statistics were used and the general linear model in the form of a repeated measures

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**Figure 1.** A schematic diagram of the virtual phantom, which was created to consist of a cylindrical-shaped PTV (diameter of 30 mm) and two cylindrical OARs (each OAR is having the diameter of 20 mm) at different locations. The dimensions of the phantom were 12 cm (length) × 30 cm (width) × 20 cm (height).
analysis of variance (ANOVA) was applied. The differences were considered statistically significant when the p-value was less than 0.05. All included variables were checked for normality. The analysis was performed by using statistical software ‘IBM SPSS Statistics for Windows’ (IBM Corp. released 2013, Version 22.0. Armonk, NY: IBM Corp.)

3. Results
All the IMRT plans from the different TPS were analysed by using the data derived from the respective DVH. From the analysis of DVH for PTV, all the planning objectives were achieved with both VMAT and HT plans. Both VMAT and HT showed good coverage of PTV with 95% of the PTV ($D_{95\%}$) receiving more than 90% of the prescribed dose. VMAT provided a significantly higher average $D_{95\%}$ (range 93.14% - 97.52%) than HT (range 90.69% - 92.85%) for all the separation groups.

However, SSIMRT plans failed to meet the planning objectives of $D_{95\%}$ when PTV and OARs are adjacent to each other ($D_{95\%}$ ranged 68.38% - 79.59%). It was generally shown that there was a significant difference among the three techniques for different separation groups of PTV and OARs. The maximum dose received by PTV for SSIMRT (range 108.12% - 108.87%) was significantly higher compared with VMAT (range 102.93% - 107.62%) and HT (range 102.67% - 104.95%). For the dosimetric results of OARs, the dose-volume objectives were met easily in all the IMRT plans.

3.1. Conformity analysis
In this study, SSIMRT plans failed to meet the planning objectives when PTV and OARs are adjacent to each other, and this is indicated by lower average CI values of 0.705 ± 0.109. The results also show that both VMAT and HT exhibited superior average CI than SSIMRT. This was echoed in the dosimetric results for PTV coverage which demonstrated that VMAT and HT plans had a higher PTV coverage. Additionally, HT had slightly better plan conformity than VMAT with the consistency of average CI value (range 1.003 - 1.028) regardless the PTV-OARs separation.

For the statistical analysis of CI, ‘one-way repeated measures ANOVA’ statistical test was used to investigate significance of CI differences in SSIMRT vs VMAT, SSIMRT vs HT, and VMAT vs HT. There was a significant difference among the three different IMRT techniques for different separation groups of PTV and OARs. When PTV and OARs are adjacent to each other, the SSIMRT yielded significantly lower CI than VMAT (0.705 vs. 1.006, $p < 0.001$) and HT (0.705 vs. 1.003, $p < 0.001$). CI was found not to be significantly different in both VMAT and HT for PTV-OARs separation of 0 - 1 cm.

4. Discussion
Generally, SSIMRT exhibited lower average CI than VMAT and HT for virtual phantoms planning. This result denoted that VMAT and HT are superior in dose conformity and all these were echoed in the dosimetric results for PTV coverage which demonstrated that VMAT and HT plans have a higher PTV coverage. The CI for VMAT plans was found to be higher than HT and was greater than 1, implying that the irradiated volume was greater than PTV. HT had slightly better plan conformity with the consistency of average CI value regardless the PTV-OARs separation.

In this simple phantom study, the conformity results for the virtual configurations did not show a clear trend favouring one delivery technique over the other. For instance, HT performed better plan conformation and showed the consistency of CI regardless the PTV-OARs separation. It was superior at sparing OAR compared with SSIMRT and VMAT, with lower volume of irradiated healthy tissue.

5. Conclusion
This study has demonstrated the conformity assessments on all the IMRT plans generated using the virtual phantoms. The results of these studies have shown for the first time, the feasibility of using the measure of CI on virtual phantoms for assessing plan conformity.
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Acknowledgements
The authors would like to thank the Director General of Health Malaysia for his permission to publish this article as well as to the staff of Nottingham Radiotherapy Centre who have provided technical support in this work.