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FULL PAPER

The role of complexity metrics in a multi-institutional dosimetry audit of VMAT

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Objective: To demonstrate the benefit of complexity metrics such as the modulation complexity score (MCS) and monitor units (MUs) in multi-institutional audits of volumetric-modulated arc therapy (VMAT) delivery.

Methods: 39 VMAT treatment plans were analysed using MCS and MU. A virtual phantom planning exercise was planned and independently measured using the PTW Octavius® phantom and seven29® 2D array (PTW-Freiburg GmbH, Freiburg, Germany). MCS and MU were compared with the median gamma index pass rates (2%/2 and 3%/3mm) and plan quality. The treatment planning systems (TPS) were grouped by VMAT modelling being specifically designed for the linear accelerator manufacturer's own treatment delivery system (Type 1) or independent of vendor for VMAT delivery (Type 2). Differences in plan complexity (MCS and MU) between TPS types were compared.

Results: For Varian® linear accelerators (Varian® Medical Systems, Inc., Palo Alto, CA), MCS and MU were significantly correlated with gamma pass rates. Type 2 TPS created poorer quality, more complex plans with significantly higher MUs and MCS than Type 1 TPS. Plan quality was significantly correlated with MU for Type 2 plans. A statistically significant correlation was observed between MU and MCS for all plans ($R = -0.84$, $p < 0.01$).

Conclusion: MU and MCS have a role in assessing plan complexity in audits along with plan quality metrics. Plan complexity metrics give some indication of plan deliverability but should be analysed with plan quality.

Advances in knowledge: Complexity metrics were investigated for a national rotational audit involving 34 institutions and they showed value. The metrics found that more complex plans were created for planning systems which were independent of vendor for VMAT delivery.

INTRODUCTION

Intensity-modulated radiotherapy (IMRT), and more recently, volumetric-modulated arc therapy (VMAT) and tomotherapy are now implemented in many radiotherapy clinics.¹ A dosimetry audit to verify treatment planning system (TPS) modelling and treatment delivery has been undertaken and its accurate clinical implementation has been demonstrated.² This type of end-to-end testing in audits has the advantage that centres can benchmark their delivery against others. However, if there are suboptimal results, it can be difficult to provide feedback on which part of the treatment chain is the cause. Therefore, further information on each stage of the treatment process including planning parameters, planning technique/class solutions,

planning optimization and deliverability is important. Differences in each of these steps may lead to plans with different degrees of complexity and could affect delivery accuracy.

A number of metrics have been used to define the complexity of treatment plans and these have been implemented for IMRT^{3,4} and more recently used as a surrogate for delivery accuracy for rotational therapies.⁵⁻⁹ Metrics have included monitor units (MUs), modulation complexity score (MCS), leaf travel and modulation index with different levels of success in correlating these with delivery accuracy. The MCS assesses plan complexity based on the variability of leaf positions, aperture area

between segments and segment weight as defined by McNiven *et al*³ and can be determined with each control point considered as a beam segment for VMAT. A number of studies observed significant correlations when comparing MCS with gamma pass rates determined using either log files or arrays.^{5,8,9} Incorporating leaf speed into the modulation index^{6,7} or using the leaf travel⁹ has proven to have higher correlations with delivery accuracy than conventional complexity metrics such as MU or MCS. MU has been used as a metric for complexity, although correlations with delivery accuracy have not been definitively demonstrated.^{5,8,9} Each investigation of complexity has used a single TPS, a single linear accelerator type and either one or two methods to record delivery accuracy. However, complexity metrics, TPS type, linear accelerator type and delivery validation method have generally varied across different studies.

With different levels of success, each study has attempted to correlate the complexity^{5–9} with delivery accuracy with the aim of identifying for which patients quality assurance is essential, hence reducing quality assurance workload. Indeed, it has been stated that it would be desirable to have measures of beam modulation to confirm whether the level of complexity of individual plans is related to the delivery accuracy and associated quality assurance metrics in credentialing.¹⁰ As yet, no investigation into complexity in a multi-institutional audit has been carried out for rotational therapies across different TPS and/or linear accelerator types.¹⁰

The aim of this study was to demonstrate the utility of complexity metrics such as the MCS and MU in multi-institutional audits of VMAT treatment delivery.

METHODS AND MATERIALS

All centres in the UK who were already treating patients with a rotational IMRT technique or were ready to start treating by March 2013 were included in this audit.² This comprised 24 centres (26 plans) with Varian® linear accelerators (Varian® Medical Systems, Inc., Palo Alto, CA) and 10 centres (13 plans) with Elekta linear accelerators (Elekta AB, Stockholm, Sweden). Only linear accelerator-based deliveries were analysed in this work as the in-house code for complexity comparisons studied had been developed for linear accelerator-based multileaf collimators (MLCs).⁵ The measurement system was the PTW Octavius II® and seven29® array (PTW-Freiburg GmbH, Freiburg, Germany).

Plans and verification

A generic plan was created by each centre on the virtual phantom shown in Figure 1 with pre-delineated volumes called the 3DTPS test.¹¹ The test included five planning target volumes (PTVs) and one organ at risk (OAR), each of which had different specified dose constraints per fraction (2.5 Gy: primary PTV2, 2.0 Gy: PTV3 and PTV5 and 1.5 Gy: PTV1 and PTV4, with maximum dose to the OAR <1.0 Gy). The plan was validated on each of the planning systems before the audit began and was designed to be challenging. Centres were asked to use their VMAT standard planning technique and TPS settings. There were no requirements on the number of arcs to be utilized for planning. Each centre was provided with a standard set of CT scans of the Octavius II phantom and was instructed to import this scan into their TPS. Each centre was instructed to apply their normal procedure for setting the size of dose calculation grid and couch correction; *e.g.* inserting or ignoring a couch structure in the planning system. (Figure 1)

Figure 1. The dimensions and positions of the three-dimensional (3D) treatment planning system volumes in a virtual cylindrical phantom in (a) the transverse plane and (b) 3D visualization. OAR, organ at risk; PTV, planning target volume.

Institutions were given detailed instructions to ensure that the position of the dose distribution relative to the phantom was consistently reproduced, and thus the dose planes were measured by the audit team using the same Octavius phantom in the same part of the plan for each centre. These consisted of two coronal (horizontal) planes and a sagittal (vertical) plane, each of which intersected a different selection of targets and critical structures.¹² Analysis of each measured dose plane was made using the PTW Verisoft® software (PTW-Freiburg GmbH). Global gamma analysis was performed by the coordinating centre, using 2%/2 and 3%/3 mm (dose difference and distance to agreement) with a minimum dose threshold of 20%. The normalization dose for the gamma analysis was inside the high-dose PTV in a low-dose gradient region.

The TPS were grouped according to whether VMAT modelling had been specifically designed for the manufacturer's own treatment delivery system [Type 1: Varian Eclipse™ (Varian Medical Systems) and Varian linear accelerators] or had been designed to be independent of vendor or VMAT delivery systems [Type 2: Monaco (Elekta AB), Oncentra (Elekta AB) and Pinnacle (Philips Radiation Oncology Systems, Fitchburg, WI) with Varian or Elekta linear accelerators]. The data were also analysed based on the delivery system. Varian linear accelerators included TrueBeams, 2100CDs, 2300IXs and a Novalis, while Elekta linear accelerators included Agilities, Synergies, MLCi2 and an Elekta beam modulator.²

Complexity and plan quality metrics

The digital imaging and communications in medicine (DICOM) plan of each 3DTPS plan submitted was used to extract the MU and MLC positions and used to calculate the MCS. The MCS uses the MLC positions of each control point, weighted by the contribution of that control point to define the leaf sequence variability (LSV) and the aperture area variability (AAV). The LSV characterizes the variability in segment shape based on the change in leaf position between adjacent leaves. The AAV characterizes the variation in segment area relative to the maximum area across all segments/control points. The MCS for each

arc is the product of the LSV and AAV weighted by the relative MU of each control point. From this definition,³ the MCS for a simple unmodulated field approaches 1, while the MCS for complex, highly modulated fields tends to 0. The total MUs were also collected for each plan as a further measure of complexity. The number of arcs and number of control points per arc were also investigated for each plan.

Each PTV in the planning exercise had a mean, minimum and maximum dose constraint, and the OAR had a single maximum dose constraint. The plan quality metric (PQM), modified from that presented by Nelms et al,¹³ was defined as Equation (1):

$$f(x) = 100 \times \frac{\text{Constraints Achieved}}{\text{Total Constraints}} \quad (1)$$

Statistical analysis

Control points, MU and MCS are presented as mean ± 1 standard deviation as they were deemed normally distributed and gamma passing rates, and PQMs are presented as median (range). The median pass rates at 3%/3 and 2%/2 mm of the three measured planes were compared with MU and MCS. Statistical analysis was carried out using MATLAB® v. R2010a (MathWorks®, Natick, MA). Pearson correlations (R) were used to describe the relationships between variables. Results were deemed correlated for $R > 0.50$. P values were calculated using the Mann–Whitney U test for gamma analysis or PQM comparisons and student t -tests for complexity metrics. Statistical significance was set at $p = 0.05$.

RESULTS

Figure 2 shows a spectrum of different complexities, defined by either the MCS or MU, which was observed across all centres when creating plans for the same virtual phantom. Figure 2(a) shows that a weak correlation ($R = 0.42$, $p < 0.01$) overall was observed between the MU and median gamma pass rate of 3%/3 mm. Figure 2(b) also shows a weak correlation ($R = 0.49$, $p < 0.01$) between MCS and median gamma pass

Figure 2. (a) Correlation of median pass rates (3%/3 mm) with monitor units ($R = -0.42$, $p < 0.01$). (b) Correlation of median pass rates (3%/3 mm) with modulation complexity score ($R = 0.49$, $p < 0.01$).

Table 1. Modulation complexity score (MCS) and monitor units (MUs) showing mean (1 standard deviation). Gamma pass rates (2%/2 and 3%/3 mm) and plan quality metric showing median (range). Also shown are Pearson correlations between MCS and MU with gamma pass rate with associated p -values with significant correlations with $R > 0.5$ in bold

Group	MCS	MU	Plan quality metric (PQM) (%)	Gamma pass rate		Correlation with MCS		Correlation with MU	
				3%/3 mm	2%/2 mm	3%/3 mm	2%/2 mm	3%/3 mm	2%/2 mm
All linear accelerators ($n = 39$)	0.226 (0.058)	760 (189)	93.8 (50.0–100.0)	99.7 (84.0–100.0)	95.5 (50.5–100.0)	$R = 0.49$ ($p < 0.01$)	$R = 0.49$ ($p < 0.01$)	$R = -0.42$ ($p < 0.01$)	$R = -0.35$ ($p = 0.03$)
Varian ($n = 26$)	0.246 (0.052)	710 (155)	100.0 (68.9–100.0)	100.0 (84.0–100.0)	97.6 (50.5–100.0)	$R = 0.68$ ($p < 0.01$)	$R = 0.52$ ($p < 0.01$)	$R = -0.68$ ($p < 0.01$)	$R = -0.38$ ($p = 0.056$)
Elekta ($n = 13$)	0.188 (0.051)	858 (216)	84.4 (50.0–100.0)	98.1 (86.9–100.0)	85.6 (55.6–100.0)	$R = 0.06$ ($p = 0.85$)	$R = 0.05$ ($p = 0.87$)	$R = -0.03$ ($p = 0.92$)	$R = -0.02$ ($p = 0.95$)
Type 1 ($n = 22$)	0.250 (0.038)	697 (111)	100.0 (81.3–100.0)	100 (95.0–100.0)	98.1 (78.6–100.0)	$R = 0.38$ ($p = 0.08$)	$R = 0.39$ ($p = 0.08$)	$R = -0.18$ ($p = 0.42$)	$R = -0.22$ ($p = 0.33$)
Type 2 ($n = 17$)	0.194 (0.065)	841 (237)	84.3 (50.0–100.0)	98.1 (84.0–100.0)	85.6 (50.5–100.0)	$R = 0.38$ ($p = 0.14$)	$R = 0.29$ ($p = 0.28$)	$R = -0.31$ ($p = 0.23$)	$R = -0.13$ ($p = 0.62$)

Varian linear accelerators, Varian® Medical Systems, Inc., Palo Alto, CA; Elekta linear accelerators, Elekta AB, Stockholm, Sweden.

rate of 3%/3 mm. However, there was an increased likelihood of lower passing rates when MU was >700 MU or MCS was <0.23 , although many plans in this range still achieved gamma pass rates $>99\%$ for 3%/3 mm. (Figure 2)

Table 1 highlights similar correlations between both MU and MCS, which were observed when the dose difference and dose to agreement were changed to 2%/2 mm. When only Varian linear accelerators were analysed, a stronger correlation between complexity and delivery accuracy was observed, and no correlation was seen for the Elekta-only analysis. The lack of correlation for Elekta-only analysis may have been due to the fact that there were only 13 centres evaluated. Correlations were very weak when plans were subdivided into Type 1 or Type 2 TPS.

Varian deliveries were composed of 4 Type 2 plans and 22 Type 1 plans. Table 1 shows that the 22 Type 1 plans did not have statistically significant correlations between complexity and delivery accuracy. However, when the four Type 2 plans were included in the Varian analysis, a significant correlation was observed due to a larger spread of complexities and pass rates.

A number of plans with intermediate complexity had acceptable gamma pass rates with the tolerance set at 3%/3 mm, but when the thresholds were reduced to 2%/2 mm, a significant increase in failed pixels was observed. The direct result of this was that the magnitude of the correlation between MCS/MU and gamma pass rate for 2%/2 mm reduced in comparison with 3%/3 mm.

Significantly lower gamma pass rates were observed for Type 2 plans compared with Type 1 plans for 3%/3 mm ($p < 0.01$) as shown in Figure 3(a). Table 1 and Figure 3(c) show that Type 1 systems produced plans with significantly fewer MUs than Type 2 plans ($p = 0.02$). Type 1 plans had significantly higher MCS than Type 2 plans ($p < 0.01$), which would again suggest that Type 1 plans are less complex as illustrated in Figure 3(d).

Each centre using the Type 1 TPS had two 360° arcs with control points equally distributed at 2° intervals. Type 2 algorithms had two 360° arcs with seven Oncentra and three Pinnacle plans utilizing control points with between 2° and 4° equally spaced intervals (one Pinnacle plan used one arc with 2° between control points). All six Monaco plans had between 54 and 158 control points per beam which were not equally spaced. Overall, Type 2 algorithms had significantly less control points per arc than Type 1 plans (98 ± 25 vs 178 ± 0 , $p < 0.01$).

The PQMs were not correlated with MCS for any group investigated. The metric was significantly correlated with MU for Type 2 planning systems ($R = 0.58$, $p = 0.02$). This suggests that plan quality reduces with reducing MU. A weak, but significant correlation between PQM and delivery accuracy was observed, although this significance no longer stood when an outlier was removed. Figure 3(b) shows that Type 1 plans were significantly better than Type 2 plans as quantified using the PQM ($p = 0.01$).

Figure 3. Box plots comparing Type 1 and Type 2 planning systems for (a) gamma passing rates of 3%/3 mm, (b) plan quality metrics and complexity using (c) monitor units and (d) modulation complexity score. Boxes represent median and interquartile range. Whiskers represent the spread of the data. The 5th and 95th percentile outliers are denoted by closed circles.

Figure 4 shows that there was a strong correlation between MU and MCS ($R = 0.84$, $p < 0.01$). This strong correlation, not always observed when assessing complexity metrics,³ may be due to the fact that the same virtual phantom and planning dose constraints were used.

DISCUSSION

It has been clearly demonstrated that even though a single set of anatomy and planning constraints was used for each centre, plans with a wide variation of complexity were observed across 34 centres. Planning systems where rotational IMRT modelling had been designed for the manufacturer's own treatment delivery system (Type 1) were significantly less complex and had significantly higher plan quality than those designed independently of rotational IMRT delivery systems (Type 2). These Type 2 systems also had significantly lower gamma pass rates following delivery to the PTW 2D array and Octavius phantom than the Type 1 systems. This is consistent with previously reported values where tomotherapy plans were also included in the analysis² and gamma pass rates were also significantly lower for Type 2 plans.

Significant correlations have previously been observed between complexity and delivery accuracy³⁻⁶ with improved metrics more recently presented.⁶⁻⁹ However, the work presented here

Figure 4. Plot of modulation complexity score against monitor units for all 39 plans. Linear regression (solid line).

is the first that compares data from a wide range of TPS manufacturers and delivery systems collected within a national audit. Overall, some correlations were observed between complexities and delivery accuracy. The most significant correlation was when only Varian linear accelerators were investigated. This correlation was less when only Type 1 TPS were used as the range of MU, MCS and gamma passing rates was less. The Type 2 planning systems or/and Elekta linacs showed no correlations between complexity and delivery accuracy. This may have been attributed to the large range of different methodologies of delivering control points and the variation in planning technique such as the number of arcs.

MU showed a weak correlation with delivery accuracy when either all linear accelerators were considered or only Varian linear accelerators were considered which was slightly higher than that reported by Agnew et al⁵ and Crowe et al⁸ and was in line with the observations by Masi et al.⁹ MCS showed similar correlations to previous observations^{5,8,9} and higher values than those observed by Park et al^{6,7} when all linear accelerators or Varian linear accelerators were considered. Masi et al⁹ showed that the angular spacing of control point can affect delivery accuracy as this was related to leaf travel. The work presented in this article showed that Type 1 plans had significantly more control points than Type 2 plans. Further work is under way to investigate complexity metrics incorporating MLC leaf speed and leaf travel using the current data set.

Correlations do not always imply a causal link. Other factors may be linked with deliverability including treatment planning parameters, couch modelling and even limitations in detectors. Both MU and MCS, and indeed any complexity metric, have limitations in the fact that they cannot include any inaccuracies in treatment planning modelling parameters such as leaf gap width, leaf leakage or couch modelling as sources of error which can significantly affect delivery accuracy.^{14,15} Different planning systems have different parameters that are required in their model.^{16,17} It is important that these parameters are evaluated prospectively or at least during follow-up of poor results in dosimetry audits of complex radiotherapy techniques, in order to assess if one of the parameters could lead to improved

modelling of the delivery. One method to check the TPS modelling is to ask centres to deliver the same plan. However, this also has limitations in that different plans would be required for a different manufacturer, different MLC type and in some cases, different linear accelerator model.

Complexity metrics have the advantage in that they can be analysed before a site visit during audits. In future audits, confidence intervals of expected MU and MCS could be created for a benchmarking planning case and any centre that submit plans which fall outside these limits could be investigated before any measurement visit to test delivery accuracy takes place. The increased complexities for Type 2 systems may be due to significant differences in TPS model implementations. The PQM analysis clearly demonstrated that higher MU for Type 2 plans resulted in plans with higher quality, and this may have been the reason for more complex plans. Therefore, any confidence interval may have to be based on the TPS capabilities.

Other potential differences in complexity and plan quality could be planner experience in inverse planning where less experienced planners may use conflicting optimization parameters, although this can be difficult to quantify.¹³ Without a planning exercise audit with feedback on complexity, it would be difficult for a single centre implementing (or have already implemented) VMAT, or IMRT, to know that their plans may be overcomplex. This study presented a framework on how this could be performed.

CONCLUSION

Complexity metrics have a role in audit as they allow centres and vendors to quantitatively assess the complexity of the plans they produce. The complexity metrics successfully differentiated between different TPS types. Quantification of plan complexity within large audits could aid improvements in planning methodologies and optimization algorithms leading to less modulated plans which could improve delivery accuracy. This information, combined with plan quality metrics and TPS modelling parameters would aid full characterization of each TPS/delivery system within a radiotherapy audit.

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