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Tomotherapy treatment site specific planning using statistical process control

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ABSTRACT

Background: This study investigated planned MLC distribution and treatment region specific plan parameters to recommend optimal delivery parameters based on statistical process techniques.
Methods: A cohort of 28 head and neck, 19 pelvic and 23 brain pre-treatment plans were delivered on a helical tomotherapy system using 2.5 cm field width. Parameters such as gantry period, leaf open time (LOT), actual modulation factor, LOT sonogram, treatment duration and couch travel were investigated to derive optimal range for plans that passed acceptable delivery quality assurance. The results were compared against vendor recommendations and previous publications.
Results: No correlation was observed between vendor recommended gantry period and percentage of minimum leaf open times. The range of gantry period (min–max) observed was 16–21 s for head and neck, 15–22 s for pelvis and 13–18 s for brain plans respectively. It was also noted that the highest percentage (average ($\bar{X}$) ± SD) of leaf open times for a minimum time of 100 ms was seen for brain plans (53.9 ± 9.2%) compared to its corresponding head and neck (34.5 ± 4.2%) and pelvic (32.0 ± 9.4%) plans respectively.
Conclusions: We have proposed that treatment site specific delivery parameters be used during planning that are based on the treatment centre and have detailed recommendations and limitations for the studied cohort. This may enable to improve efficiency of treatment deliveries by reducing inaccuracies in MLC distribution.

1. Introduction

Treatment delivery quality assurance (QA) is a key step during pre-treatment checks to verify the accuracy of dose delivered to the patient for complex treatments such as intensity modulated radiation therapy (IMRT) [1]. IMRT treatments involve the use of non-uniform beam intensities to provide high dose to clinically designated target volumes and spare adjacent critical organs due to their improved ability to conform dose distributions to the PTV [1–3]. In addition to recent advances in the engineering of linear accelerators, the design of multi-leaf collimators (MLCs) has also improved in providing targeted treatments to suit radiotherapy treatment needs. In recent times treatment planning systems (TPS) that provide IMRT plan optimisation often provide MLC modelling capabilities to encompass the complexity of their design effectively to treatment dose.

Helical tomotherapy is different from conventional modulated radiotherapy as it is capable of producing dose conformality by combining continuous gantry rotation, treatment couch translation and MLC leaf movement during treatment using a rotational fan-beam geometry [4–8]. Hi-Art II TomoTherapy (Accuray, Inc., Sunnyvale, CA) uses a flattening-filter free 6MV linear accelerator, a pneumatically controlled 64 leaf binary MLC and a xenon filled CT detector mounted on a slip ring gantry providing a fan-beam treatment delivery [9–11]. Unlike conventional linear accelerators, the target to isocentre distance is 85 cm, and the machine output is measured in cGy/min at the depth of dose maximum at the isocentre [9,12]. An integrated treatment planning system uses the system output measurement to account for the various treatment parameters e.g., MLC delivery sinogram, leaf open time (LOT), couch velocity and gantry rotation period and projection for its maximum 40 × 5 cm field size defined at the machine isocentre. For every 360-degree gantry rotation, the number of treatment beam projections based on the MLC pattern is fixed at 51, with each

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projection equating to a 7 degree gantry arc [8]. During each projection, the duration of the LOT is primarily determined by the plan's modulation factor (MF), which is defined as the ratio of the maximum LOT in a given plan to the average non-zero LOT for that plan. This parameter limits the allowable range of LOTs used during treatment [8,11,13]. Each plan has MLC leaf instructions in the form of a two-dimensional data array called a fluence sinogram, that lists the planned intensity for each projection [8,11].

The xenon filled CT detector also known as the MVCT detector is primarily used with a 3MV imaging beam to verify pre-treatment patient positioning, however it can also be used to monitor daily machine output and treatment beam output during patient delivery [1,5,7,14,15]. A planned fluence MLC sinogram consists of information concerning the energy fluence and LOT [8,15]. A verification sinogram consists of actual MLC projections versus the leaf number [8,11,15]. The planned LOT sinogram (or planned sinogram) indicates the amount of time each binary leaf is open relative to the total projection time in the form of a two-dimensional array, that is, it represents leaf or detector intensity values as a function of beam angle. A sinogram can contain data for up to 1800 projections or more based on target coverage. Each projection is then converted into a set of segments by identifying the largest continuous group of adjacent leaves producing sinogram segments and splitting the projection by the amount of the segments in the sinogram.

Quality control of processes is essential in radiotherapy treatment systems to document, correct and improve system performance [16]. Control charts in statistics are used to monitor a process over time. The fundamental principle of using quality control is to observe historical performance of existing systems and predict their future behaviour. Statistical process control (SPC) is one such tool that identifies if the current system is stable for the system to operate with efficiency using its recommended tolerance levels [12,14,17].

Numerous studies [1,3,7,11,15,18,19] have investigated the variations between planned and delivery MLC sinograms to evaluate the cause of MLC fluence discrepancies during treatment delivery. However, there is no consensus based on statistical process control methods to determine the range of MLC planning parameters such as: LOT, projections, MF, planned sinogram and resultant treatment parameters such as couch travel, gantry period, pitch and duration. Those studies have also indicated that variations in the method of analysis and positioning of isocentre depending on the treatment site can produce different QA results.

This study utilises statistical process control methods on a cohort of pre-treatment verification plans such as: head and neck, pelvis and brain to recommend upper and lower control limits for planning parameters relating to MLC distribution to predict delivery accuracy during QA for the assessed machine site.

2. Methods

A total of 28 head and neck, 19 pelvic and 23 brain pre-treatment plans were selected for this study and delivered on a Hi-Art II helical tomotherapy system. All treatment sites were planned on the Tomotherapy TPS v4.2 using the same field width (FW) of 2.5 cm and were in accordance with the Radiation Therapy Oncology Group (RTOG) clinical prescription guidelines and IMRT planning was performed as per constraints proposed in QUANTEC. Pre-treatment verification was performed using the ArcCHECK 3D diode array (Sun Nuclear Corporation (SNC), Melbourne, FL) and an Exradin A1SL ionisation chamber (Standard Imaging, Middleton, WI) placed at the centre of the ArcCHECK in a polymethyl methacrylate (PMMA) cylinder for relative fluence and absolute dose measurements respectively. The delivery QA process involved re-calculating the planned volume of interest in the centre of the ArcCheck and a comparing with a corresponding absolute measurement in this region of interest using a centrally placed ionisation chamber [10,11]. The clinical criterion for clinically acceptable delivery performance using gamma analysis metric in the SNC Patient software v6.2 on the phantom plans calculated by the TPS v4.2 software was set at ≥ 95% gamma tolerance using Van Dyk (using global percentage difference normalisation to the maximum planned point dose) ± 3% dose, distance to agreement (DTA) of 3 mm and a dose difference threshold of 10%. Plans with a lower clinical pass criterion were investigated to rule out uncertainties due to detector resolution and/or a re-optimisation/re-batching of beamlets were recommended till a satisfactory clinical pass was achieved. The latter did not involve using a systematic approach requiring the need to assess plans individually based on their MLC distribution. This study has used a cohort of plans that consist of gamma results within a range of 90–100 %, this criterion was selected to investigate optimal planned MLC parameters in addition to absolute point dose difference tolerance (between measured and planned distribution) of ± 3%.

An optimal gantry period of 20 s is recommended by the vendor [8], who reported that this can improve treatment efficiency and reduce treatment duration and stress on the treatment machine components while maintaining the same treatment goals. Several papers have recommended optimal pitches for different planning scenarios [20,21], however the general recommendation from the vendor to minimise treatment time is to start with an initial pitch of 0.43 for all plans. The MLCs takes approximately 10–20 ms to transition from the open to closed state or vice versa, known as leaf latency. This latency is measured during commissioning and is taken into account in the planning system. However due to mechanical limitations of the machine and signalling delays associated with the MLC electronics overtime, differences between planned and actual leaf latencies occur [3]. To reduce the impact of these discrepancies between planned and measured doses, it is recommended that the short LOTs are minimised where possible such that the percentage of LOTs approaching the minimum limits (< 100 ms × total number of fractions) is less that 40–50% [22]. Mechanical limitations of leaf motion and signalling delays associated with MLC electronics can cause differences between planned and actual leaf latencies.

Statistical process control techniques[17] in addition to data correlation analysis using Welch's *t*-test [23,24] were used to identify optimal delivery values such as: LOT, projection, duration and sinogram segments, etc. Control charts [25] were plotted for all assessed delivery parameters to determine random and systematic discrepancies in the treatment delivery or planning process. A centre line (CL) defines the mean of the dataset ($\bar{X}$) or process and an upper and lower control limit (UCL and LCL) determine the range of the data spread based on Eqs. (1)–(3) [26].

$$UCL = \bar{X} + 2\frac{\bar{mR}}{d_2\sqrt{n}} \quad (1)$$

$$CL = \bar{X} \quad (2)$$

$$LCL = \bar{X} - 2\frac{\bar{mR}}{d_2\sqrt{n}} \quad (3)$$

In Eqs. (1)–(3), R indicates the range of the group, d_2 denotes a constant dependent on a continuous set of n measurements. For this study only one group was considered for each analysis, hence n is 1 and d_2 is 1.128 [27]. The moving average range, $\bar{mR}$ is the absolute difference between two consecutive measurements ($mR_i = |x_i - x_{i-1}|$).

Using this technique, a control chart was obtained such that the CL is a reference for the data point dispersion and points outside the UCL and LCL indicate the process to be out of control due to systematic reasons. When the data fall within the UCL and LCL, the process is considered within control with only random causes affecting the process [25,27]. The UCL and LCL were set at ± 2 standard deviations from the mean such that the range would include 95% of data points if the distribution is normal.