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The use of a realistic VMAT delivery emulator to optimize dynamic machine parameters for improved treatment efficiency

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Abstract

The delivery of volumetric modulated arc therapy (VMAT) requires the simultaneous movement of the linear accelerator gantry, multi-leaf collimators and jaws while the dose rate is varied. In this study, a VMAT delivery emulator was developed to accurately predict the characteristics of a given treatment plan, incorporating realistic parameters for gantry inertia and the variation in leaf speed with respect to gravity. The emulator was used to assess the impact of dynamic machine parameters on the delivery efficiency, using a set of prostate and head and neck VMAT plans. Initially, assuming a VMAT system with fixed dose rate bins, the allowable leaf and jaw speeds were increased and a significant improvement in treatment time and average dose rate was observed. The software was then adapted to simulate a VMAT system with continuously varying dose rate, and the increase in delivery efficiency was quantified, along with the impact of an increased leaf and jaw speed. Finally, a set of optimal dynamic machine parameters was derived assuming an idealized scenario in which the treatment is delivered in a single arc at constant maximum gantry speed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In recent years there has been increasing interest in the use of dynamic arcs rather than static beams to deliver radical radiotherapy (Yu and Tang 2011). While commercial planning and delivery solutions for arc therapy are still relatively in their infancy, a number of studies have already demonstrated significantly reduced treatment times without compromising the dose distribution when compared to fixed-field intensity modulated radiotherapy (IMRT)

(Matuszak *et al* 2010, Palma *et al* 2008). Planning solutions for sites such as the prostate (Zhang *et al* 2010, Wolff *et al* 2009), head and neck (Bertelsen *et al* 2010, Vanetti *et al* 2009) and lung (McGrath *et al* 2010, Verbakel *et al* 2009) have been demonstrated, indicating that arc therapy may be able to at least complement the provision of IMRT in the radiotherapy department.

Volumetric modulated arc therapy (VMAT) refers to the delivery of dose using a conventional linear accelerator moving in an arc around the patient. The field shape, defined by multi-leaf collimators (MLCs) and jaws, is dynamically varied during the arc along with the dose rate and gantry speed to produce an intensity-modulated dose distribution (Otto 2008, Cao *et al* 2009). VMAT delivery often requires only one complete arc around the patient, although larger and more complex treatment sites may require more (Guckenberger *et al* 2009). A number of authors have reported a delivery time benefit of 50–100% compared with fixed field IMRT (Zhang *et al* 2010, Verbakel *et al* 2009, Shaffer *et al* 2009).

When formulating VMAT as a method of delivering IMRT in a single arc, Bortfeld and Webb (2009) describe both techniques as having compromises: standard IMRT can produce highly modulated fields, but from a coarse sampling of fixed gantry angles, whereas VMAT uses all gantry angles but has no instantaneous modulation. A further practical limitation of VMAT is that adjacent control points ('segments') around the arc must be achievable with the linear accelerator. That is, the linac control system must be able to move the MLCs, jaws and gantry, whilst modulating the dose rate, in order to deliver the correct dose. In theory, for finite leaf and jaw speeds, the linac should be able to deliver any control point provided it is able to reduce the gantry speed and dose rate low enough. Practically, however, very low dose rates are undesirable in VMAT delivery due to their impact on treatment time efficiency—widely reported as the most significant advantage of this technique. While good dosimetric results have been demonstrated on plans utilizing a large range of dose rates, adverse effects on the beam stability, flatness and symmetry have also been observed at very low rates (Bedford and Warrington 2009).

In order to ensure delivery efficiency, many planning systems for VMAT include delivery constraints within the optimization. The method described by Otto (2008), which is now part of the Varian RapidArc system, incorporates factors such as the maximum leaf speed and gantry speed into the optimization algorithm. These 'efficiency constraints' ensure that the dose rate on the machine is maximized for each control point. Similar constraints are used within the Philips Pinnacle³ SmartArc system (Bzdusek *et al* 2009). SmartArc requires user-inputted values for maximum allowable leaf, jaw and gantry speed, as well as the minimum and maximum number of MUs per gantry angle degree. Users can also specify the maximum leaf travel per gantry degree, and can specify a maximum delivery time.

Successful dosimetric verification has been demonstrated with both RapidArc and SmartArc on Varian and Elekta linear accelerators (Rao *et al* 2010, Feygelman *et al* 2010). However, the impact of a linac's dynamic parameters (leaf, jaw, gantry speed and dose rate) on delivery efficiency has not yet been fully characterized. This paper considers this problem through the use of a realistic VMAT delivery emulator and a cohort of plans. Machine constraints were adjusted within the software and by modelling the delivery, their effect on treatment efficiency was investigated. Initially, the existing Elekta VMAT system, which uses fixed dose rate bins, was considered and the impact of adjustments to the leaf and jaw speed was assessed. The effect of continuously variable dose rate was then investigated to quantify the time advantage when using a larger number of dose rate bins. Finally, the emulator was used to model a scenario in which treatment is delivered in a single arc at constant gantry speed. This represents a fast and highly efficient method of delivery, limited only by the maximum allowable gantry speed of the linac.

2. Materials and methods

2.1. VMAT system

The VMAT system described in this paper consists of the Pinnacle³ v.9.0 SmartArc planning module, and delivery with an Elekta Synergy linear accelerator (RTD v.6.0). Plans produced using SmartArc are exported to a record and verify system (MOSAIQ) via an ‘RTP’ file, which contains the instructions for the linac (gantry angle, MLC and jaw positions, and monitor units for each control point).

In order to achieve delivery of the control points, the linac is able to adjust the gantry speed and dose rate. Elekta linacs were previously only able to choose from a fixed set of dose rate bins, from the machine’s maximum decreasing by a factor of 2 (e.g. 600 MU min⁻¹, 300 MU min⁻¹, 150 MU min⁻¹, 75 MU min⁻¹ etc). The linac will preferentially deliver dose at the highest rate possible, but will step down to a lower bin to satisfy the maximum gantry speed constraint, and to allow time for the leaves and jaws to reach their next position. The latest release of the Elekta VMAT system allows for continuously variable dose rate. Rather than the 4–5 fixed bins described above, the linac will be able to choose from 255 dose rates up to the maximum.

2.2. Development of emulator

Software was written in Java which emulates the VMAT delivery. There are three main stages for the emulator: firstly, the software reads in a VMAT RTP file and builds a set of instructions for the linac. Secondly, the software interprets the instructions and calculates the appropriate gantry speed and dose rate bin for each control point (figure 1).

Initially, the gantry speed required to deliver the prescribed number of MU at the maximum dose rate is calculated. If this gantry speed exceeds the physical limit of the machine, then the dose rate is dropped to a lower bin and the speed is recalculated:

$$\Omega_G = \frac{\Delta^\circ}{(\Delta\text{MU}/\text{DR}_{\text{bin}})} \leq \Omega_G^{\text{max}} \quad (1)$$

where Ω_G is the gantry speed (°/s), Δ° is the gantry angle interval, ΔMU is the control point MU, DR_{bin} is the current dose rate bin (MU/s) and Ω_G^{max} is the maximum allowable gantry speed. Using this value for gantry speed, the time for the control point can be calculated ($t_{\text{cp}} = \Delta^\circ/\Omega_G$). The emulator then calculates how much time the leaves and jaws require to travel from their previous position to the current control point:

$$t_{\text{lim}} = \max\left(\frac{\Delta L_{\text{max}}}{v_{\text{leaf}}}, \frac{\Delta J_{\text{max}}}{v_{\text{jaw}}}\right) \quad (2)$$

where t_{lim} is the limiting time, ΔL_{max} and ΔJ_{max} are the maximum leaf and jaw distances to travel (cm) and v_{leaf} and v_{jaw} are the nominal leaf and jaw speeds (in cm s⁻¹). The emulator evaluates t_{cp} and t_{lim} , and ensures that the condition $t_{\text{cp}} > t_{\text{lim}}$ is met by stepping down to a lower dose rate bin if necessary and re-evaluating equation (1). This process is repeated over all the control points, and the emulator outputs the gantry speed and dose rate.

In the final module of the software, the target gantry speeds and dose rate bins are sent to a realistic machine emulator, which models the actual delivery characteristics. The model includes

- (a) the acceleration or deceleration of the gantry between control points;
- (b) the variation in the *actual* leaf speed with respect to gravity around the arc;
- (c) the acceleration and deceleration of the leaves.

Figure 1. Flowchart describing the emulator software process.

The models for each of these parameters were derived from actual machine measurements using the Elekta ‘service graphing’ function. This is a software tool accessible within the service mode of the linac, which allows various machine parameters (e.g. gantry position) to be logged during delivery, with a time resolution of 250 ms. The log files can later be interrogated to determine the machine state at a given point in the delivery, including the dose rate, leaf, jaw and gantry speed.

Details of the model parameters are found in table 1. The nominal maximum leaf and jaw speeds (v_{leaf} and v_{jaw}) are intentionally set lower than the actual speeds (which vary from 2.2 to 3.4 cm s⁻¹ depending on the MLC orientation with respect to gravity). This is done to ensure that t_{cp} is very often greater than t_{lim} , i.e. the MLCs reach their required position well before the gantry has reached the next control point. The emulator software monitors the number and magnitude of leaf-positioning problems, and records an ‘error’ if a leaf is >1 mm from its intended position at the end of the control point. The emulator ultimately outputs the gantry speed and dose rate bin for each control point, along with the delivery time.

The emulator was assessed for accuracy by comparing its output to the actual machine deliveries for a range of patient plans. For these commissioning tests, the

Table 1. List of values used to model the linear accelerator within the emulator. The values were derived from experiments on an Elekta Synergy linac. It was estimated that each of the simplifying assumptions will contribute $\ll 0.1$ s error in the calculation of each control point.

Machine parameter	Magnitude in the emulator model	Notes and model assumptions
Gantry acceleration	$1.8\text{--}3.2^\circ \text{ s}^{-2}$	Varies with gantry angle
Gantry deceleration	$3.4\text{--}4.3^\circ \text{ s}^{-2}$	Varies with gantry angle
Leaf speed	$2.2\text{--}3.2 \text{ cm s}^{-1}$	Varies with gantry angle. At gantry angle 0° , assume opposing leaf banks are identical, and speed of leaf motion inwards = speed outwards
Leaf acceleration and deceleration time	0.25 s	Assume acceleration = deceleration, and no impact due to MLC orientation with respect to gravity

software constants were set to the same as the actual linac control system: $v_{\text{leaf}} = 2.0 \text{ cm s}^{-1}$, $v_{\text{jaw}} = 2.0 \text{ cm s}^{-1} \Omega_G^{\text{max}} = 6^\circ \text{ s}^{-1}$ (this gantry speed limit is specified by the IEC standard 60601). The realistic machine parameters were set as in table 1. A ‘benchmarking’ cohort of ten Pinnacle-planned VMAT treatments (five prostate and five head and neck) was delivered on an Elekta Synergy linac and live parameters were recorded using the service graphing function. The measured parameters were then plotted against the emulator’s output and the overall treatment time was compared.

2.3. Virtual experiments

Experiments using the emulator were performed with a separate ‘experimental’ cohort of ten VMAT plans (again consisting of five prostate and five head and neck). The single-arc prostate plans (mean 474 MU) were created according to the local three-dose level protocol for VMAT. The head and neck plans (all oropharynx treatments with mean 533 MU) were produced on patients previously treated with IMRT. They consisted of two counter-rotating arcs, and aimed to achieve a dose distribution which approximates the IMRT solution. Each plan was exported to MOSAIQ and the RTP file was retrieved for input into the emulator.

2.3.1. Effect of dynamic parameters on treatment efficiency. The first experiment examined the impact of leaf and jaw speed on the duration and efficiency of delivery. Maximum gantry speed was held constant for these tests, and dose rate bins were fixed at 600, 300, 150 and 75 MU min^{-1} . For each plan, the emulator was run for various values of v_{leaf} and v_{jaw} , with the corresponding ‘real’ parameter adjusted by the same margin. Delivery time was calculated, as well as the percentage of monitor units delivered in each dose rate bin.

2.3.2. Effect of continuously variable dose rate. A modification to the software allowed the emulator to select a much greater range of dose rates, as in the recent Elekta VMAT update. 255 dose rate bins were allowable, up to the maximum dose rate (in this case set at

600 MU min⁻¹). The treatment time reduction was quantified for the plan cohort, and again the impact of increasing v_{leaf} and v_{jaw} was investigated.

2.3.3. Determining ‘ideal’ machine parameters. The minimum possible delivery time for a single 360° arc is 60 s (based on the IEC-defined maximum gantry speed of 6° s⁻¹). If Ω_G^{max} is set to 6° s⁻¹ in equation (1), then for each control point

$$\text{DR} = \frac{\Delta \text{MU}}{(\Delta^\circ/6)}. \quad (3)$$

This requires a continuous range of deliverable dose rates in order to maintain constant gantry speed (as ΔMU is a continuous variable). It can therefore be seen that, in order to satisfy the requirement $t_{\text{cp}} > t_{\text{lim}}$

$$v_{\text{leaf}} > \frac{\Delta L_{\text{max}}}{(\Delta^\circ/6)} \quad \text{and} \quad v_{\text{jaw}} > \frac{\Delta J_{\text{max}}}{(\Delta^\circ/6)} \quad (4)$$

which is true for both leaf motion and jaw motion. For the cohort of five prostate and five head and neck plans, these parameters (maximum dose rate, leaf speed and jaw speed) were calculated in order to achieve the required maximal delivery time. The effect of increasing the number of bins from 255 to 1023 was also assessed.

3. Results

3.1. Commissioning results

When compared to actual deliveries on the linac, the emulator produced realistic results. A typical comparison is shown in figure 2(a), demonstrating that the emulator selects the appropriate dose rate bins as the treatment progresses. Over five prostate VMAT plans, the emulator treatment time differed from the actual time by an average of -1.5 s (± 1.4 s 1SD) for each beam. For the head and neck patients, the difference was -3.9 s (± 1.2 s) per arc. Figure 2(b) shows a comparison between the emulator and the actual machine when gantry position is plotted against time. The complete data of timing comparisons are shown in table 2. Mean delivery time, as determined by the emulator, was 116.1 s for the prostates and 239.9 s for the dual-arc head and neck patients.

3.2. Virtual experiments

3.2.1. Effect of dynamic parameters on treatment efficiency. For the single-arc prostate treatments, the effect of increasing the allowable leaf speed is shown in figure 3. A leaf speed increase from 2.0 to 3.0 cm s⁻¹ reduced the delivery time by an average of 21.0 s. Beyond 3.0 cm s⁻¹ there was no significant time reduction. Figures 3(b) and (c) demonstrate how with an increased leaf speed the linac was able to select higher dose rate bins for delivery. The mean dose rate was increased from 294 MU min⁻¹ at 2.0 cm s⁻¹ to 351 MU min⁻¹ at 3.0 cm s⁻¹. The number of monitor units delivered in the top dose rate bin increased by an average of 13.8%, and the histogram also shows a reduction in the number of MUs delivered in the lower dose rate bins.

For the head and neck plans, an increase in maximum leaf speed of 2.0–3.0 cm s⁻¹ reduced the average delivery time by 37 s for the first arc and 42 s for the second arc. Figure 4(a) shows that this time improvement was due to the linear accelerator being able to select 150 MU min⁻¹ rather than 75 MU min⁻¹. The histogram of MUs delivered in each dose bin shows a significant positive shift with increased leaf speed (figure 4(b)).

Figure 2. (a) Comparison of the emulator-predicted dose rate against time versus the measured dose rate on the machine, for a typical prostate plan. (b) For the same plan, a comparison of the gantry position with time demonstrating the agreements between the emulator and the linac measurements.

The mean dose rate increased from 144 to 199 MU min⁻¹, while the number of MUs being delivered in the lowest bin (75 MU min⁻¹) was reduced by 25%.

When assessing the impact of leaf speed changes on the realistic delivery parameters, no leaf-positioning errors were recorded when increasing the nominal leaf speed from 2.0 to 3.0 cm s⁻¹, provided the actual leaf speed increases by the same amount. Furthermore,

Table 2. Comparison of the total delivery times between the linac and the emulator for the cohort of benchmarking plans.

Prostate	Emulator time (s)	Linac time (s)
1	113.4	117.3
2	114.3	115.8
3	116.7	117.5
4	113.4	114.5
5	122.5	122.8
Mean	116.1	117.6
Head and Neck		
1	125.9 + 123.4	129.5 + 125.5
2	114.3 + 104.9	120.3 + 108.3
3	125.6 + 121.2	130.0 + 126.5
4	122.5 + 115.6	126.8 + 119.0
5	124.4 + 121.5	128.8 + 123.8
Mean	122.5 + 117.3	127.1 + 120.6

the estimated leaf acceleration/deceleration time of 0.25 s needs to be maintained if leaf-positioning errors are to be avoided.

In contrast to leaf speed, the maximum jaw speed was not a limiting factor in any of the plans considered in this study. The magnitude of jaw position changes between control points was small compared to leaf position changes, and so when evaluating equation (2) the limiting leaf travel time was always greater than the limiting jaw travel time. Increasing jaw speed had no effect on any of the plans, and so no data are presented.

3.2.2. Effect of continuously variable dose rate. With 255 dose rate bins, the treatment time was significantly reduced when using the parameters of $v_{\text{leaf}} = 2.0 \text{ cm s}^{-1}$, $v_{\text{jaw}} = 2.0 \text{ cm s}^{-1}$, $\Omega_G^{\text{max}} = 6^\circ \text{ s}^{-1}$. Figure 5 shows how the linac was able to select a much higher range of dose rates. For the five prostate patients, the average reduction in delivery time was 31.7 s and the average dose rate increased from 294 to 376 MU min⁻¹. For the head and neck patients, the delivery time advantage was 43 s per arc compared to the standard binned dose rate system, representing a 35% reduction in overall treatment time.

Increasing the maximum leaf speed with continuously variable dose rate had a similar effect of reducing the delivery time and increasing the average dose rate. Figure 5(b) shows that the reduction in delivery time peaks at a leaf speed of 3.0 cm s⁻¹, where the time benefit was ~13 s compared to 2.0 cm s⁻¹. The average dose rate also increased from 376 to 436 MU min⁻¹. For head and neck patients, increasing to 3.0 cm s⁻¹ reduced each arc time by 19 s and increased the average dose rate from 202 to 262 MU min⁻¹.

With such a significant decrease in the time per control point, leaf-positioning errors were observed if the acceleration/deceleration time was kept at 0.25 s. On average, each delivery had 8.8 control points where at least one leaf was >1 mm from its intended position by the time the gantry reached its next position. Reducing the MLC acceleration/deceleration time to 0.2 s reduced the number of errors to zero in all the plans.

Figure 3. Increasing the nominal leaf speed from 2.0 to 3.0 cm s^{-1} for the prostate patients: (a) averaged over all patients, the maximum time advantage is 21 s, (b) comparing the selection of dose rate bins over a typical treatment (prostate patient 3), (c) demonstrating that, with a higher nominal leaf speed, the linac preferentially selects higher dose rate bins.

Figure 4. Increasing the nominal leaf speed from 2.0 to 3.0 cm s⁻¹ for the head and neck patients: (a) averaged over all patients, the maximum time advantage is 79 s in total over both arcs, (b) comparing the selection of dose rate bins over a typical treatment (first arc of head and neck patient 3), (c) demonstrating that the linac preferentially selects higher dose rate bins, such that, in this example, no dose is delivered in the bottom dose rate bin.

Figure 5. Continuously variable versus binned dose rates. (a) Typical head and neck beam delivered with binned and continuously variable dose rates, where all other parameters (including leaf speed) are kept constant. (b) Time advantage when increasing nominal leaf speed with continuously variable dose rate.

3.2.3. Determining ‘ideal’ machine parameters. Applying equations (3) and (4) to the prostate and head and neck plans gave the results shown in table 3. For the five prostate plans, a maximum dose rate of approximately 1400 MU min^{-1} , a nominal leaf speed of 2.8 cm s^{-1} and a jaw speed of 1.5 cm s^{-1} were required to deliver the plan at a constant gantry speed of 6° s^{-1} . For head and neck treatments, the maximum dose rate needed to be approximately 1180 MU min^{-1} , with a nominal leaf speed of 2.8 cm s^{-1} and a jaw speed of 2.0 cm s^{-1} . These

Table 3. Idealized machine parameters for the ten VMAT plans.

	Ideal max dose rate (MU min ⁻¹)	Ideal max leaf speed (cm s ⁻¹)	Ideal max jaw speed (cm s ⁻¹)	Delivery time with emulator (s)
Prostate				
1	1392	2.8	1.5	61.4
2	1392	2.8	1.5	61.5
3	1392	2.8	1.5	61.5
4	1404	2.8	1.5	61.5
5	1386	2.8	1.5	61.4
Mean	1393	2.8	1.5	61.5
Head and Neck				
1	1119	2.8	1.8	62.1 + 62.4
2	1171	2.8	1.8	62.1 + 62.1
3	844	2.8	1.8	62.2 + 62.1
4	1104	2.8	1.8	62.2 + 62.2
5	933	2.8	1.8	62.1 + 62.4
Mean	1034	2.8	1.8	62.1 + 62.2

values were entered into the emulator to calculate the resulting delivery times, which are also shown in table 3.

Again, leaf-positioning errors were observed due to the significantly shorter control point time. On average, across the 10 patients, 12.7 control points contained positioning errors >1 mm. When the acceleration/deceleration time for the leaves was reduced from 0.25 to 0.2 s, the number of errors returned to zero.

4. Discussion

VMAT introduces a set of specific and unique problems for linac-based radiotherapy. Whereas static fields require modelling of beam profiles and modifiers within the planning system, dynamic arcs also require knowledge of the dynamic capabilities of the machine—particularly if the delivery time is to be optimized during planning. With the availability of variable dose rates, it also becomes more important to ensure that the linac delivery is efficient. Furthermore, the linear accelerator design (including the leaf, jaw and gantry speed) may not currently be optimized for VMAT delivery. The purpose of this study was to better understand the impact of these dynamic machine parameters on VMAT treatment delivery.

The emulator produced reasonable predictions of the actual delivery of the linear accelerator. While a number of realistic parameters were added to improve the accuracy of the model, some simplifying assumptions were made. The emulator assumes an idealized picture of the dose rate—that it is constant for each control point and bin switching is instantaneous—whereas it is apparent from the linac plot in figure 2 that it is not. Furthermore, the service graphing function will likely include measurement dead time, which has not been measured or accounted for in this study. These factors may explain the discrepancies between the real and predicted delivery times. Finally, it should be noted that the leaf acceleration/deceleration time was estimated at ~0.25 s, based on an average of measurements with a range 0.22–0.30 s. This is similar to the minimum resolution of the measurement, such that the real

acceleration/deceleration may at times be greater, and therefore the average value of 0.25 s represents a conservative estimate.

Rangaraj *et al* (2010) have previously investigated the properties of VMAT delivery through the use of an ideally efficient formulation of the RapidArc delivery process. Large discrepancies (>10 s) were found between the predicted and actual treatment times for five plans—a point which the paper acknowledges may be due to the lack of a full characterization of all of the constraints on VMAT delivery. In this study, the optimal (or ‘ideally efficient’) plan is subject to discretization of the dose rates (whether 4 or 255 bins), nominal and actual leaf speed constraints and the acceleration/deceleration of the gantry. Inclusion of these factors has led to accurate modelling of VMAT delivery, and also allowed investigations into the effects of changing real machine constraints.

Increasing the allowable leaf speed means that t_{lim} is reduced, allowing the linac to select higher dose rate bins and a faster gantry speed. Using the emulator allowed the efficiency to be quantified for a number of VMAT patient plans. Figure 3 shows that an improvement in efficiency is seen even with a modest increase in leaf speed. For prostates, increasing the leaf speed to 2.5 cm s^{-1} increases the number of monitor units in the top dose rate bin by approximately 10%. Similarly, for the head and neck patients, increasing the leaf speed to 2.5 cm s^{-1} reduced the proportion of MUs delivered in the bottom dose rate bin (75 MU min^{-1}) to almost zero for the five plans considered. For the prostate and head and neck patients, the maximal time advantage was achieved with a leaf speed of 3.0 cm s^{-1} .

It is important to emphasize again that the nominal maximum leaf speed of 2.0 cm s^{-1} is a conservative value stored within the software of the linac, and actual leaf speeds are greater. Thus, a v_{leaf} of 3.0 cm s^{-1} will actually require a real speed of between 3.2 and 3.8 cm s^{-1} (depending on the MLC orientation with respect to gravity). It may be feasible for manufacturers to achieve these speeds, given that the current maximum speed measured on the Elekta machine in this study was 3.4 cm s^{-1} . For Varian linacs, the nominal leaf speed has been reported to be 2.9 cm s^{-1} (Feygelman *et al* 2010), whereas the Siemens 160 MLC can achieve a maximum of 4.3 cm s^{-1} (Tacke *et al* 2008).

Continuously variable dose rate is a recent addition to the Elekta VMAT system. As expected, increasing the number of available dose rate bins to 255 significantly reduced the treatment time using the emulator. It will be of future interest to compare the results presented here to actual measurements on a continuously variable dose rate system. Again, it was found that increasing the leaf speed enabled a higher average dose rate and shortened treatment time for prostates and head and neck plans.

In principle, the fastest delivery time for a single arc is 60 s, assuming the delivery is limited only by the IEC maximum gantry speed of 6.0° s^{-1} . It was calculated that a linac would need to be able to deliver $\sim 1400 \text{ MU min}^{-1}$ for prostate plans and $\sim 1180 \text{ MU min}^{-1}$ for the head and neck plans in order to deliver at the maximum gantry speed. These dose rates are significantly higher than those used for the majority of linac-based radiotherapy. However, higher dose rates have been achieved by removing the flattening filter in the head of the linac. In particular, Cashmore (2008) reports an increase of 2.3 times the maximum dose rate for an open field. Further work would be required to assess whether VMAT could be delivered using a flattening filter-free beam, in order to facilitate maximum gantry speed delivery.

It is of interest to note that the quoted delivery times as estimated by the emulator are slightly greater than 60 s (table 3). One reason for the discrepancy is the gantry acceleration time at the beginning of the beam. However, when looking at the emulator’s predicted output over the course of treatment (figure 6), it appears that the gantry speed fluctuates between 5.8 and 6° s^{-1} . The use of an 8 bit variable for the dose rate (giving a range of 255 possible values) may not approximate well to a truly continuous variable, especially if the maximal dose rate

Figure 6. Comparison between the required gantry speeds for 8 bit (255 values) and 10 bit (1023 values) dose rate bins, for an idealized machine that can deliver $\sim 1180 \text{ MU min}^{-1}$.

is high. Increasing the bin range to 1023 values (10 bit) reduces the delivery time per arc by approximately 1 s and allows for a higher and smoother gantry speed (figure 6).

Using a software emulator has enabled an analysis of the relative importance of different dynamic delivery parameters. It will be of future interest to use the emulator to aid the planning process as well. The SmartArc plans used in this study were all subject to ‘efficiency constraints’ with the aim of ensuring deliverability and dosimetric quality on the linac. It is not clear to what extent these constraints affect the plan quality, although limiting leaf travel between control points will inevitably restrict the shapes of segments that can be selected. Using the emulator as a testing tool, it will be of interest to investigate the deliverability of increasingly unconstrained and complex plans. Treatment efficiency may then be predicted, as will any potential errors, which could then be fed back to planning in order to improve the balance between plan quality and deliverability.

5. Conclusion

Through the use of a realistic delivery emulator and a set of treatment plans, the impact of a range of dynamic parameters has been assessed for the Elekta VMAT system. Increasing the maximum MLC speed led to an increase in the number of monitor units delivered at higher dose rates, and significantly reduced the overall treatment times. The efficiency improvement due to continuously variable dose rate was also quantified for a cohort of prostate and head and neck plans. Finally, the required dose rate, leaf and jaw speeds were calculated for an idealized delivery scenario where the gantry maintains a constant maximum gantry speed of 6° s^{-1} .

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