Note: Gating Characteristics of an Elekta Radiotherapy Treatment Unit Measured with Three Types of Detector

Short title: Gating Characteristics of an Elekta Radiotherapy Treatment Unit

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Abstract. The characteristics of an Elekta Precise treatment machine with a gating interface were investigated. Three detectors were used: a Farmer ionisation chamber; a MatriXX ionisation chamber array and an in-house, single pulse-measurement ionisation chamber (IVC). Measurements were made of dosimetric accuracy, flatness and symmetry characteristics and duty cycle for a range of beam-on times and gating periods. Results were compared with a standard un-gated delivery as a reference. For all beam-on times, down to 0.5 s, dosimetric differences were below ±1 % and flatness and symmetry parameter variations were below ±1.5 %. For the shorter beam-on times the in-house detector deviated from the other two detectors, suggesting that this device should be used in conjunction with other detectors for absolute dosimetry purposes. However it was found to be useful for studying gated beam characteristics pulse by pulse.

1. Introduction

Recent research in radiotherapy physics has sought to characterise and correct for the effects of motion of the treatment target in the breathing patient for treatment sites such as the lung (Berbeco et al. 2005, Shirato et al. 2006) and liver (Wagman et al. 2003). This work has studied the effects of motion on various stages of the treatment process, including the generation of 4D CT for treatment planning (Keall et al. 2004), the use of adaptive planning to combine the effects of scans acquired on different days (Martinez et al. 2001), tracking of the motion using the delivery system (McQuaid et al. 2009) and gating of the delivery system (Kubo and Hill 1996). This note is relevant to the latter.

The objective of treatment gating is to control the treatment machine to deliver radiation at a certain part of the breathing cycle with the goal of reducing the internal motion margin (ICRU 1999) and with the potential to reduce the volume of normal tissue irradiated to high dose. Questions to be considered include the duty cycle of the gated beam and the dosimetric accuracy of the gated treatment compared with the standard, non-gated beam delivery. This may be quantified in terms of total dose delivered, beam shape (i.e. flatness and symmetry) and beam energy. The detailed measurement of these quantities on a treatment machine delivering several hundred pulses per second is challenging.

Previous authors have reported gating results for three manufacturers: Varian (Kubo and Wang 2000 and Jin and Yin 2005); Siemens (Kriminski et al. 2006 and Weibert et al. 2009) and Brainlab (Hugo et al. 2003 and Verellen et al. 2003). The Varian system uses a gridded gun for gating. In this work we evaluate the gating characteristics of the Elekta Precise system (Elekta, Crawley, UK) which is gated using a different method, interruption of the RF source during the beam-off period. We present dosimetric measurements of linac performance evaluated for a set of gating sequences, with a set of detectors, including a purpose-built ionization chamber capable of measuring single pulses at 400 pulses per second (PPS – the PRF (Pulse Repetition Frequency) of the Precise system).

2. Methods

All measurements were carried out on an Elekta Precise treatment machine, operated at 6 MV and 400 PPS. A pre-production gating interface was installed on the machine, between the linac control system and the interface cabinet. This enabled gating of the beam by interruption of the PRF chain using a TTL (transistor-transistor logic) signal input via an interface, with low voltage for beam-off and high for beam-on. In clinical use this third party interface would receive a signal which is a surrogate for patient motion, such as from an ABC (Active Breathing Control) device (Wong et al. 1999). For this work, a function generator was used (33250A, Agilent Technologies, Santa Clara, CA, USA) to enable testing with various gating schemes as discussed below.

Measurements of beam characteristics were made with three types of detector. The first was a Farmer ionisation chamber (Nuclear Enterprises type 2561, 0.6 cm^3) which was used dose measurement and TPR20/10 measurement (IAEA 2000) to detect beam energy changes. For the dose measurements the chamber was placed at the isocentre at 4 cm depth with 6 cm backscatter in a solid water phantom of area 30x30 cm^2 and irradiated with a 30×30 cm^2 field. An ungated irradiation of 50 MU was used as reference and all gated dose measurements analysed as a percentage change from the reference dose value for 50 MU. All measurements were the average of two irradiations. The charge measured for the reference irradiation was 11.10 nC. For the TPR 20/10 measurement, a 10×10 cm^2 field size was used, for standard, ungated delivery and for gated delivery with 0.75 s beam on time and 3 s period. 50 MU were delivered for each measurement. The results of three irradiations were averaged. The use of ionisation chambers to measure gated deliveries has previously been reported in the literature (e.g. Kubo and Wang 2000 and Wiersma and Xing 2007).

The second detector was a MatriXX multiple channel ionisation chamber array (IBA Dosimetry, Schwarzenbruck, Germany) which is a device of proven dosimetric accuracy that allowed dose, flatness and symmetry measurement (Herzen et al. 2007). The detector consists of an array of 32×32 chambers with a centre spacing of 7.6×7.6 mm^2, and a water equivalent measurement depth of 3.3 mm. The detector was placed on the treatment couch at the isocentre. A field size of 20×20 cm^2 was used to ensure the field edges could be seen in the data collected, to enable confirmation of the radiation field centre in the data. Irradiations were measured in movie mode, acquired as a sequence of 1s frames and the frames summed using Omnipro I'mRT software (IBA Dosimetry, Schwarzenbruck, Germany) to produce a cumulative dose image. The MatriXX has a maximum sampling speed of 20 ms. As with the Farmer chamber, measurements were made as deviations from the reference, ungated irradiation. This was achieved by dividing each gated image by a reference, ungated image to yield a corrected image. All irradiations were 50 MU. Beam flatness and symmetry were analysed by dividing the corrected image into regions to mimic the segments of the linac's ionisation chamber, i.e. a central region to measure 'hump' inner, 4 sectors to measure G, T, A and B and an outer region ('hump' outer). Hump is a measure of beam shape difference between centre and edge (and hence an indication of energy), G, T are Gun and Target directions and A, B are orthogonal directions left to right (with the gantry at zero degrees). The regions are illustrated in figure 1a. The central 18×18 cm^2 of the images was used to exclude penumbra. The average intensity in a 3×3 cm^2 central region was used for hump inner, a 1cm wide square strip at the edge was used for hump outer and the four segments G, T, A and B were calculated as the average of the four quadrants of the region between the inner and outer hump regions.

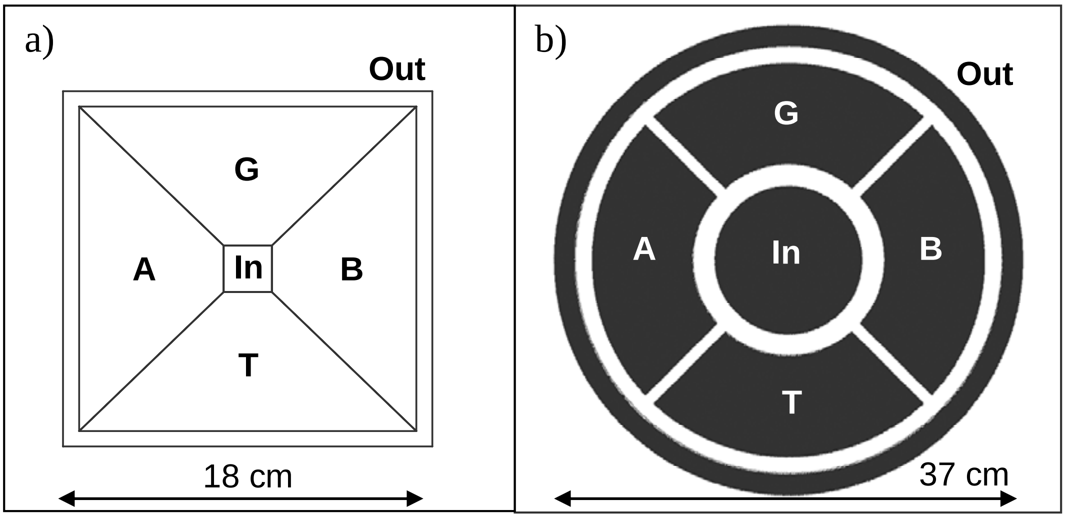

Figure 1: measurement areas of a) the MatriXX detector and b) the IVC detector. 'In' and 'Out' are the inner and outer regions for hump measurement. G, T, A and B denote the Gun, Target, A and B directions respectively.

The Third detector was an in-house pulse-measurement ionisation chamber and is a development of a large area ionization chamber we have described previously (Partridge et al. 1999). The new chamber is a parallel plate ionisation chamber, with 4.5 mm plate separation. It has entrance and exit cover plates of 0.2 mm tin-plated steel. It has an aluminium foil electrode made of a set of segments ('hump' inner/outer, G, T, A and B as in the MatriXX analysis) to mimic the geometry of the segments in the linac's ionisation chamber (see figure 1b). This detector was read by a pulse electrometer system based on IVC102 charge-to-voltage converter ICs (Texas Instruments, Dallas, TX, USA). The electrometer had a galvanically isolated input from the scope trigger signal of the linac for synchronisation. This detector is referred to as the IVC chamber. The detector was mounted in a standard Elekta accessory tray and has a field of view, projected to the isocentre, of 37 cm. For analysis of data from this detector, a 100 MU irradiation was delivered and the total charge detected (1.96 μC) was used to provide a dose calibration. The integrated signal from each of the six beam profile measurement plates, after the beam reached its nominal dose rate, was used to calibrate the reference Hump, GT and AB signals. Test irradiations were carried out with 50 MU irradiation for ungated and gated delivery and all dose deviations measured relative to the total signal for 50 MU ungated and all Hump, GT and AB deviations measured relative to the reference values. The IVC detector had the advantage of single pulse readout. However, no claims are made for its absolute dosimetric accuracy and it is an in-house device not generally available, hence its use was intended primarily to analyse the pulse by pulse behaviour of the gated linac, with the other two detectors providing the main dosimetric analysis of gating performance.

The main use of gating in radiotherapy is in response to breathing motion and this has been measured to have a period of 3-5 s (Lujan et al. 1999, Wagman et al. 2003, Berbeco et al. 2005, Shirato et al. 2006). Also treatment beam duty cycles between 20 and 90 % have been discussed (Berbeco et al. 2005, Shirato et al. 2006). In this work two experiments were carried out. Experiment one evaluated a range of periods (3, 5 and 7 s) and a range of duty cycles (25, 50 and 75 %). In the second experiment, a short beam on time of 0.5 s was investigated, with a range of periods (1, 3 and 5 s). All deviations in dose, hump value and GT and AB, flatness and symmetry were calculated relative to the reference dataset.

The measured duty cycle was obtained as the ratio of the beam on time for ungated delivery to the measured beam on time (obtained from the IVC data). This was compared with the ‘set’ duty cycle equal to the ratio of gated beam on time to gating period.

3. Results

Figure 2 illustrates IVC measurements of the delivery pulse by pulse. Charge per pulse for ungated delivery is shown in 2a, the corresponding hump and symmetry in the GT and AB directions are shown 2b. The equivalent data for 1.25 s on and 5 s period are shown in 2c and 2d. In 2c the charge per pulse increases rapidly then dips down during each gating cycle. Gated deliveries with all beam-on times showed similar behaviour and those with longer beam-on times showed that the charge per pulse dampens towards unity after 1.25s. Figure 2d shows that the GT and AB values are slightly above unity, immediately the beam comes on and converges to unity, resulting in a small error compared to an ungated delivery. Delivery with other gating parameters showed similar behaviour. The data in figures 2a and 2c are normalised to the charge per pulse for the ungated delivery once the beam has settled (15-19 s in 2a) 2b and 2d are normalised to the ungated values during the same period.

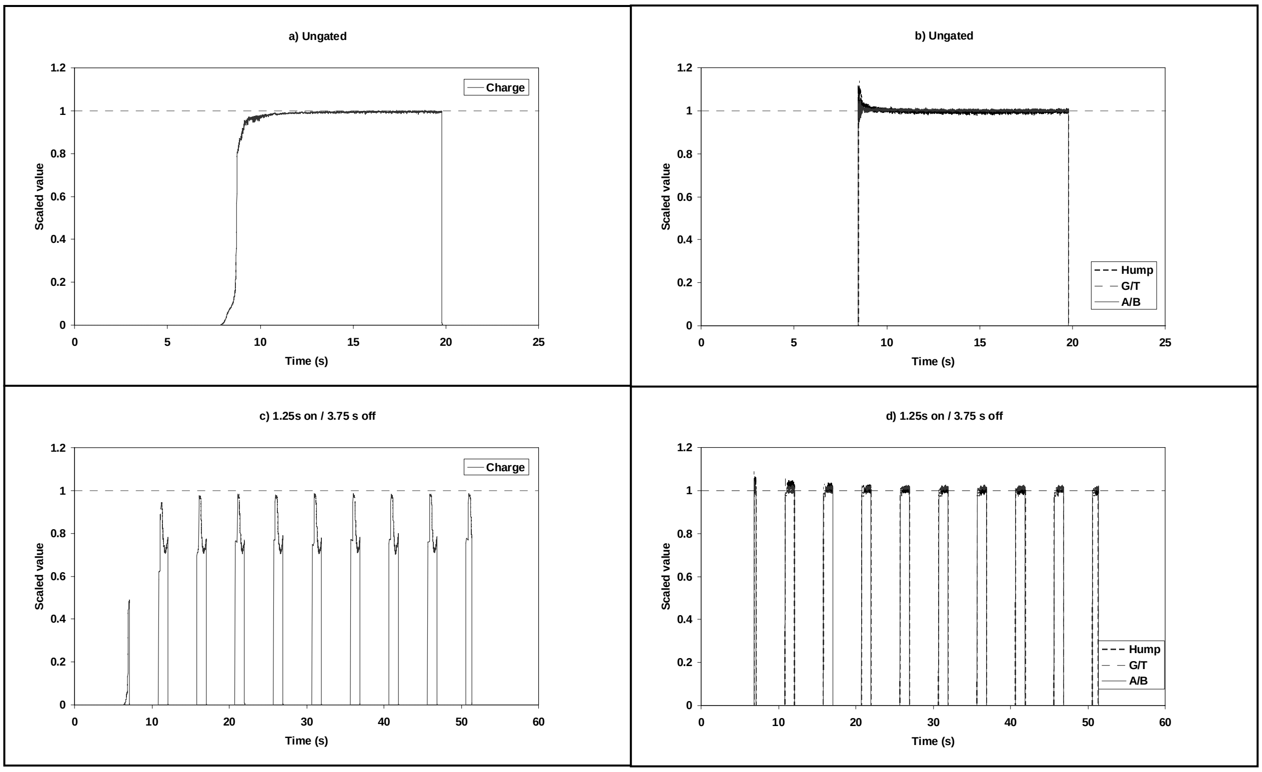

Figure 2: Example acquisition from the IVC pulse-measurement ionisation chamber for ungated (a and b) and 1.25 s on and 5 s period (c and d). a and c show charge per pulse measurement (normalised to

the nominal value for an ungated delivery) and b and d hump and symmetry in the GT and AB directions. The horizontal line shows the ideal value for both parameters of 1.

Figure 3 shows dosimetric error for the gating parameters investigated. The left side shows experiment one and the right side (separated by the thick dotted line) experiment two. For all gating parameters, Farmer and MatriXX show a difference between gated and ungated doses of less than 1 %. For experiment one, in all but one data point (1 s on time / 5 s period) IVC measurements agree to better than ±1 %. For experiment two, IVC shows a large measured underdosage. Comparison with Farmer and MatriXX suggest this is an artefact of the IVC chamber rather than the delivery system. These results show that the variations in charge per pulse shown in figure 2 does not result in dose errors or change clinical performance of the machine.

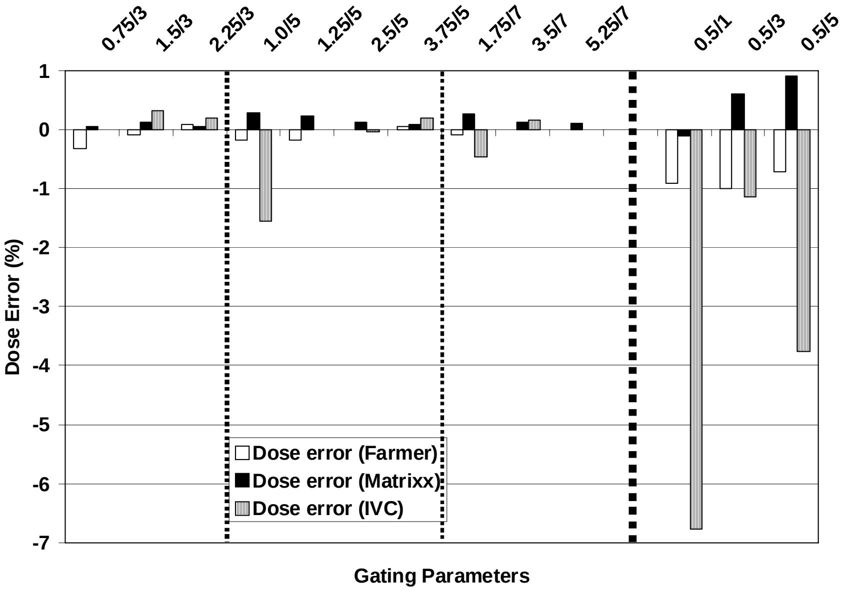

Figure 3: Dose error measurements relative to ungated delivery. Each position on the x-axis corresponds to a single gating parameter, e.g. “1.5/3” is 1.5 s on and 3 s period. The left side shows results for experiment one, with the thin dotted vertical lines separating different periods. The right side shows experiment two, with the thick dotted vertical line separating experiments 1 and 2.

Figure 4 shows the results of the Hump, AB and GT measurements. Figure 4a shows the MatriXX measurements and 4b shows IVC measurements. Both detectors show flatness and symmetry parameters deviating from the nominal values by not more than ±1-1.5 % in the vast majority of cases.

Figure 5 shows a two-dimensional plot of the flatness variation measured with MatriXX for 1.25 s on and 5 s period. This data was generated by dividing the pixel value at each point by the corresponding value for the ungated treatment. A small tilt in AB and GT is seen of no more than ±1 %.

Duty cycle was measured by comparing beam on time for the reference, ungated delivery and each gated delivery. Timing was obtained from the IVC detector. Figure 6 shows ‘efficiency’ plotted against planned duty cycle, where efficiency is defined as the ratio of the measured duty cycle to that planned. As might be expected, the measured duty cycle was smaller than the planned value due to the finite time it takes the beam to reach full (ungated) dose per pulse after each interruption.

For the TPR 20/10 measurement, the value for ungated delivery was 0.679 (±0.001) and 0.677 (±0.001) for gated delivery, suggesting no significant energy change.

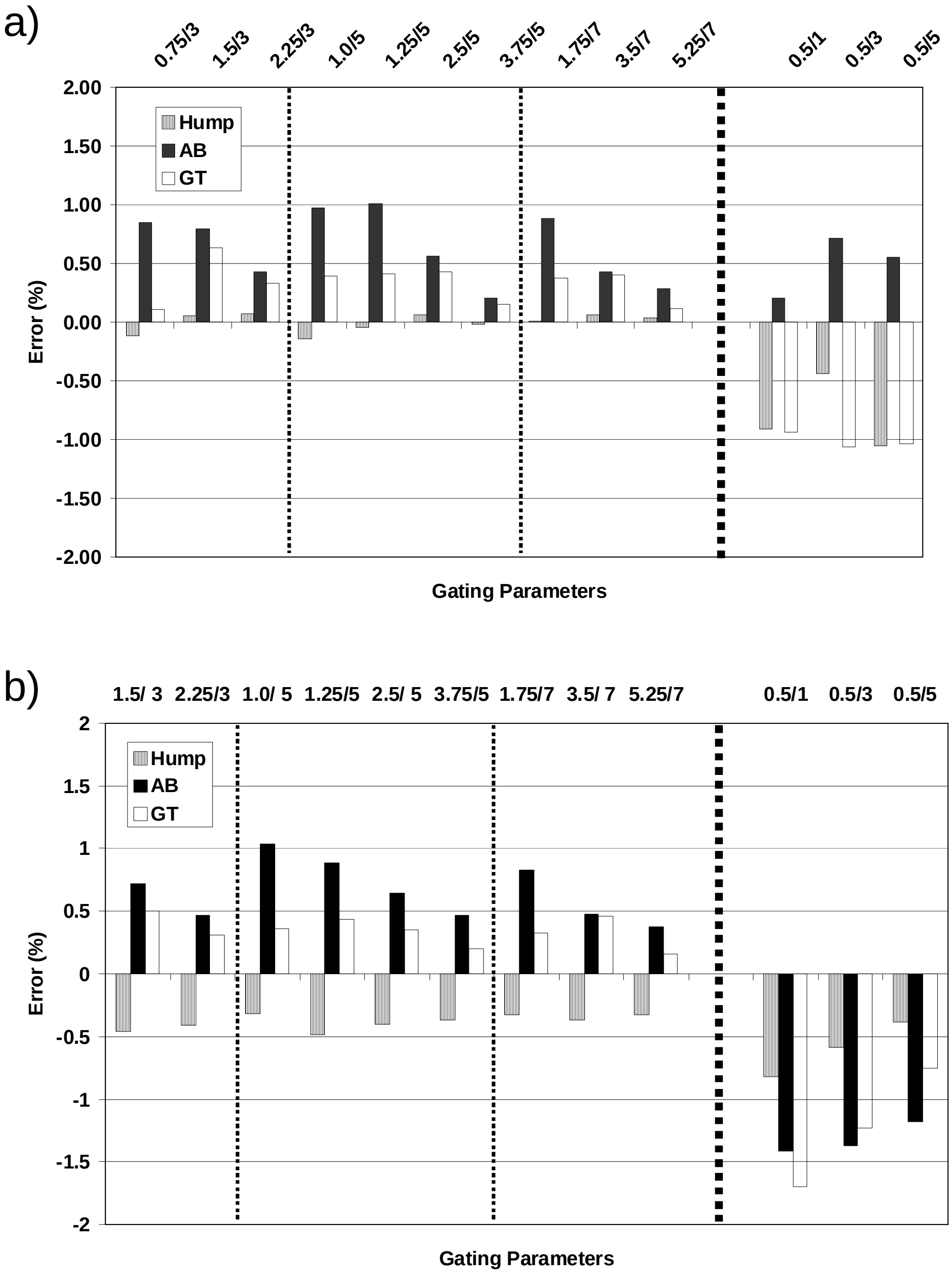

Figure 4: Flatness and symmetric metrics, measured with MatriXX (a) and IVC (b). All results are percentage changes from the reference, ungated values. The thick dotted vertical line separates data from experiments 1 and 2. The thin dotted vertical lines separate different periods in experiment 1.

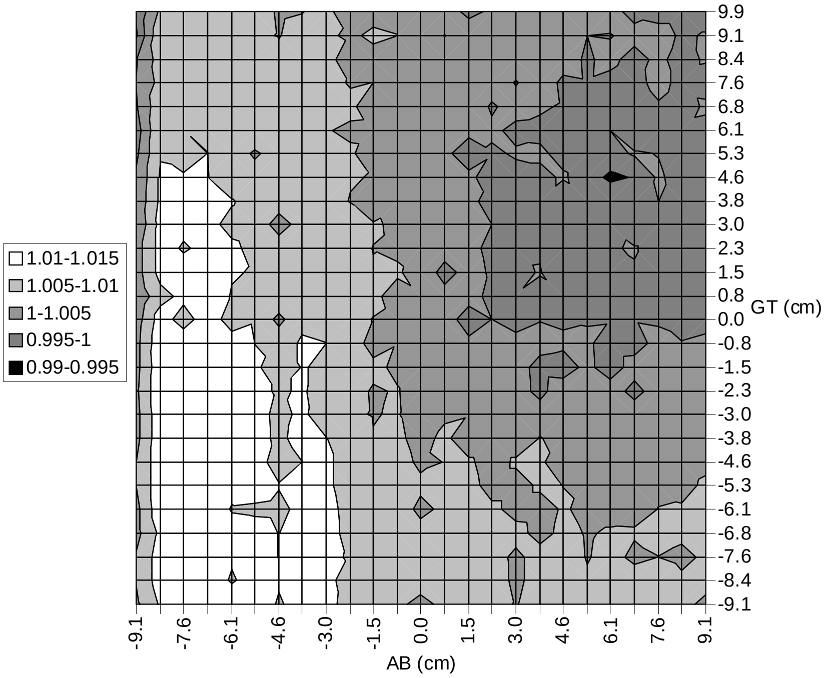

Figure 5: Plot of spatial flatness variation from the MatriXX detector for 1.25 s on and 5 s period. Data are shown for the central 18×18 cm^2 region.

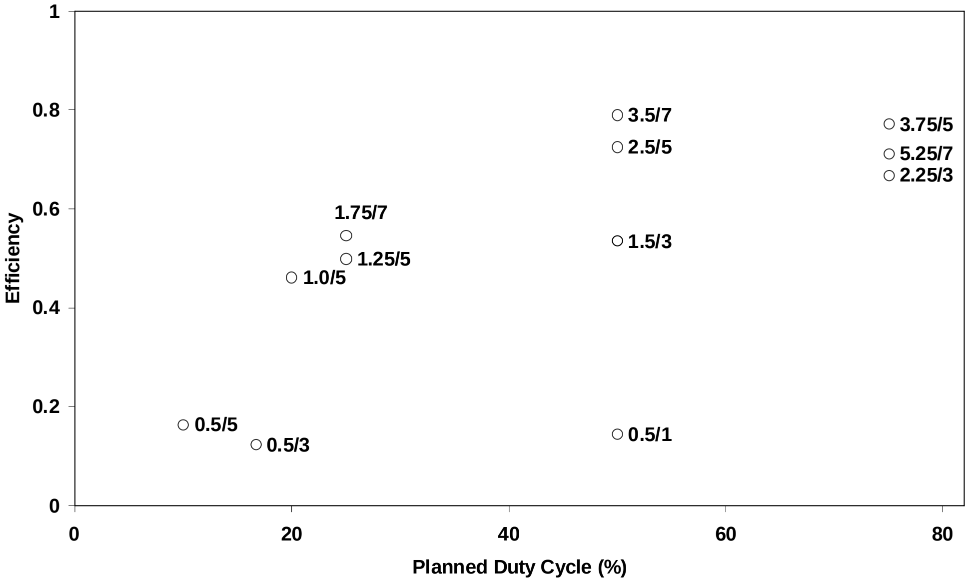

Figure 6: Plot of efficiency as a function of planned duty cycle. Efficiency is defined as the ratio of the measured duty cycle to the planned value. The labels show the parameters for each data point, e.g. 0.5/3 denotes 0.5 s on and 3 s period.

4. Discussion and Conclusions

The results show all measurements with a beam on time of more than 1 s to have a dosimetric error of better than ±1 % and the flatness and symmetry measures to be within 1.5 %. For beam on times of 0.5-1 s, the Farmer chamber and MatriXX measurements show errors still within ±1 %, with the IVC chamber measuring a larger underdosage, suggesting the IVC is under-reading the dose. In summary these results support the use of gating on the Elekta equipment with a beam on time of 0.5 s or greater and indicate that for the absolute values of the IVC chamber to be reliable, the beam on time must be greater than 1 s.

In a paper on the Varian gating system, Kubo and Hill (1996) reported a 0.1 % dose difference for 50 % duty cycle, 1.1 % inplane (GT) symmetry and 0.6 % crossplane (AB) uniformity. They also present a breathing trace with a 4 s period. In this study (for 50 % duty cycle and periods of 3, 5 and 7 s) dosimetric errors were -0.1, 0.0 and 0.0 % respective for Farmer and 0.1, 0.1 and 0.1 % respectively for MatriXX. The symmetry measured with MatriXX was 1.0 % or better in AB and 0.6 % or better in GT. IVC measurements were similar for experiment 1. Experiment 2 showed GT and AB values of up to 1.5 % in magnitude with AB changing sign. Thus these measurements are consistent with the Varian data. Kriminski et al. (2006) studied gating of the Siemens ONCOR system. They also studied a range of gating periods with 50 % duty cycle. They found dosimetry better than 0.5 % for all periods greater than 2 s (0.5 Hz in their results). For a 2 s period, errors of ±1 % or greater were observed in some, extreme, cases. Other work on Varian equipment has studied the effects of the dose rate for a sequence of step and shoot segments (Wiersma and Xing 2007). Their results showed the variation between the segments to increase with dose rate. For this work here we used the fastest dose rate available.

The work presented here is preliminary in that it is the first study of a dedicated gating interface to an Elekta Precise system. Questions still to be addressed include measurement and minimisation of the latency between the onset of the gating signal and the halting of beam delivery (Jin and Yin 2005).

The gating interface requires an input that is a surrogate for the patient’s breathing phase in order to deliver an accurate treatment. This is not addressed in this study, but a good candidate is the ABC (Active Breathing Control) device (Wong et al. 1999). This could be used to gate delivery in conjunction with a set of long breath holds controlled by the device and used to trigger gating. This would result in a long beam-on time for which the gating interface is expected to produce good dosimetric accuracy. However the need for extra image guidance should be considered (Korreman et al. 2008).

Duty cycle is compromised by gating to some extent, although figure 6 shows this is likely only to become problematic for very short beam-on times of 0.5 s or less. For example, a 100 MU ungated delivery was timed at 5.7 s. For a beam-on time of 1.5 s and period of 3 s, this would increase to 20.7 s. These short on times are likely to not be clinically relevant due to the extended treatment delivery time and the marginal incremental improvement in conformality. The use of breath holds and audio-visual coaching would be expected to reduce this problem by allowing greatly increased beam-on times (Linthout et al. 2009).

In conclusion we have evaluated the use of a pre-production gating interface for the Elekta Precise treatment machine. Results show good dosimetric accuracy and beam shape characteristics for a range of gating parameters. These parameters: 1 s to 7 s beam-on time and 10 % duty cycle for the shortest beam-on time, extending beyond values likely to be encountered clinically (e.g. Lujan et al. 1999, Wagman et al. 2003, Berbeco et al. 2005, Shirato et al. 2006). An in-house developed pulse-measurement ionisation chamber was compared with two standard dosimeters. Results showed the in-house device agreed with the standard devices to within 1 % for all but the most extreme gating parameters. The deviation for the shortest gating times is under investigation.

Acknowledgements

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