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REPORT ON DOSE MEASUREMENTS ON THE ELEKTA UNITY MR-LINAC AT THE ROYAL MARSDEN HOSPITAL PERFORMED BY NPL

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Report on dose measurements on the Elekta Unity MR-linac at The Royal Marsden Hospital performed by NPL

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ABSTRACT

This report describes measurements of the radiation dose from the MR-linac at The Royal Marsden Hospital, Sutton using a selection of detectors (such as ionisation chambers and alanine) in order to calibrate the machine output. Absorbed dose to water calibration coefficients for the ionisation chambers used in the MR-linac machine when the constant magnetic field was either on (1.5 T) or off (0 T) were also determined. Together with similar measurements performed at NPL in a 0 T magnetic field over a range of beam qualities, the corrections required to measure the absorbed dose in the presence of a magnetic field using these detectors can be determined.

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1 INTRODUCTION

MRI-guided radiotherapy (MRIgRT), a state-of-the-art cancer treatment, combines a linear accelerator (linac) with a Magnetic Resonance Imaging (MRI) scanner. An MRI-linac provides real-time images during a patient's treatment and greatly enhanced soft-tissue image contrast, while completely avoiding the radiation dose associated with X-ray systems. MRIgRT is expected to improve real-time adaptive planning based on high-contrast moving visual images of the change of the tumour characteristics and explore the possibilities of an advanced personalised radiotherapy.

While great benefits for cancer treatment are anticipated using this new technology, there are, however, issues that need to be addressed. Among them is the effect of the external magnetic field (B-field) on the dose distribution in water and dosimeters. Although the photon beam is not affected by the B-field, the direction of motion of the secondary electrons is changed (known as electron return effect, ERE). The affected trajectories of these electrons is known to modify ion chamber sensitivity and the absorbed dose distribution in water (Raaijmakers *et al.*, 2005, Raaijmakers *et al.*, 2007, Raaymakers *et al.*, 2004, O'Brien *et al.*, 2016).

Measurements and Monte Carlo (MC) calculations have previously been made to characterise the response of different types of ionisation chambers (Meijsing *et al.*, 2009, Smit *et al.*, 2013, O'Brien *et al.*, 2016, Reynolds *et al.*, 2013, Spindeldreier *et al.*, 2017). These works investigated the optimal chamber orientation with respect to the B-field and radiation beam, parallel (||) or perpendicular (⊥), as well as the B-field correction factors at different field strengths. Considering the change in the chamber response relative to a B-field strength of 0 T, these studies found that when the ionisation chamber axis is:

- (⊥) to the B-field and the radiation beam is (⊥) to the B-field, the change is ranging from 4% - 11.3%.
- (||) to the B-field and the radiation beam is (⊥) to the B-field, the change is <1%.
- (||) or (⊥) to the B-field and the radiation beam is (||) to the B-field, the change is <1% for a B-field strength up to 1 T and increases to approximately 2% at 1.5 T.

The B-field correction factor (which is explained in section 2.8), for different types of ionisation chambers, is ranging from 0.992 to 1.005 when the chamber is parallel to the B-field and 0.953 to 0.976 when the chamber is perpendicular to the B-field.

The aim of this work was to make measurements using both an Ion Beam Applications (IBA) and a Physikalisch-Technische Werkstätten (PTW) Farmer-type chamber and alanine/EPR dosimeters (Electron Paramagnetic Resonance), in determining correction factors and the optimum setup for Farmer-type chamber-based dosimetry in the Elekta MR-linac at The Royal Marsden Hospital (RMH), Sutton. The measurements involved determining beam output as well as calibration coefficients, by substitution, for each of the ionisation chambers.

The change in sensitivity of an air-filled ion chamber due to the ERE in a 1.5 T B-field strength depends on the chamber cavity size and shape and is expected to vary with chamber type. A study by Gallas *et al.* (Gallas, 2017) investigated the change in the sensitivity of alanine due to the ERE by varying the air gap around the alanine pellets inside the pellet holder. They found that the ERE does not affect the dose readout of alanine.

The EPR readout signal from an alanine dosimeter is proportional to the number of stable free radicals resulting from previous irradiation of the alanine. Strong B-fields can be expected to modify diffusion and recombination of ions in irradiated alanine and so the free radical yield may be sensitive to the B-field strength at the time of irradiation. The sensitivity of alanine in terms of absorbed dose to water as a function of B-field strength has been measured at the United Kingdom National Physical Laboratory (NPL) over a range from 0 T to 2 T, using a General Motors Worldwide (GMW) type 3474-140 electromagnet at two different beam qualities (^{60}Co and 8 MV linac beam). Results have shown that the strong B-field in an MR-linac has a small effect on the sensitivity of alanine in terms of absorbed dose to water. A B-field correction factor of 0.996 (for 1.5 T B-field strength) has been applied to all alanine dose measurements. The correction factor is mostly dominated by the effect of the B-field on the absorbed dose to water. This correction factor was determined by interpolating the MR-linac beam quality (at RMH) to the ^{60}Co and 8 MV beam qualities.

Alanine has a weak beam quality dependence in its sensitivity, and produces a slightly smaller signal for a given dose when irradiated by megavoltage X-rays compared to ^{60}Co radiation. A correction factor of 1.004 has been included in all the alanine dose measurements reported here.

The alanine dosimetry system, as well as one of the PTW Farmer-type ionisation chambers (sn: 03981) and the IBA Farmer-type ionisation chambers (sn: 3520) used in this investigation have been calibrated at NPL. The calibration was performed in a conventional Elekta Synergy linac (zero B-field strength), for a range of megavoltage X-ray beams between 4 MV and 18 MV, and in ^{60}Co radiation, traceable to the NPL reference standard of absorbed dose to water.

Measurements were also performed at the MR-linac at Christie Hospital, Manchester (including a Farmer-type chamber from RMH). The purpose of this visit was to determine the absorbed dose to water calibration coefficient, for each dosimeter used, in the constant magnetic field of the MR-linac. Three of the ion chambers used have previously been calibrated using the Netherlands' primary standard water calorimeter from the Van Swinden Laboratory (VSL) in the Elekta MR-linac at the University Medical Center Utrecht (UMC-U) in the Netherlands. The three ion chambers serve as a transfer standard in this work, providing traceability to the VSL primary standard. Results of this visit can be found in NPL Report IR 50.

The combination of the results from the current report and NPL Report IR 50, will give for each ionisation chamber used the:

1. Calibration coefficients traceable to an MR-linac via an ionisation chamber.
2. Calibration coefficients traceable to a conventional linac via alanine dosimetry (in both 0 T and 1.5 T B-field strength).
3. Determination of the magnetic field correction factor, k_Q^B.
4. Machine calibration using NPL's alanine dosimetry for each visit.

2 MATERIALS AND METHODS

Measurements were made in the MR-linac facility at RMH and in a conventional linac at NPL (zero B-field strength). Measurements at NPL include calibration of NPL's Farmer-type chambers in a range of different beam qualities. Chambers were also calibrated at the Elekta MR-linac at Christie Hospital using transfer detectors directly calibrated against the VSL's primary standard water calorimeter. The methodology used and the results can be found in NPL Report IR 50.

Three visits were accomplished at the MR-linac at RMH, dated:

1. 13 – 14 February 2017
2. 14 – 15 March 2017
3. 24 – 25 May 2017

On the 1st and 3rd visit the constant B-field of the MRI scanner was ramped down (0 T). On the 2nd visit, the B-field was switched on and measurements were performed at 1.5 T. Results are presented for each visit.

Absorbed dose was measured per MU:

- at the isocentre

- in a static horizontal (gantry angle = 90°, 3rd visit) and vertical beam (gantry angle = 0°, 1st and 2nd visit), with the detector axis perpendicular to the beam and parallel to the B-field.
- in a field size of 10 cm x 10 cm at the measurement plane
- in a 1D water tank (PTW MP1/T41052) provided by RMH
- at a water-equivalent depth of 10 cm and 20 cm

The following dosimeters were used:

- PTW waterproof Farmer-type chamber (type 30013)
- IBA waterproof Famer-type chamber (type FC65-G)
- Alanine (seven of 5 mm diameter and 2.5 mm thick pellets in a waterproof Farmer-shaped polyether ether ketone (PEEK) holder)

Each dosimeter is located in its own holder in the water tank.

2.1 SET UP IN THE MR-LINAC

Measurements were performed using a water tank, which was placed on the couch table inside the bore of the MRI scanner (Figure 1.a).

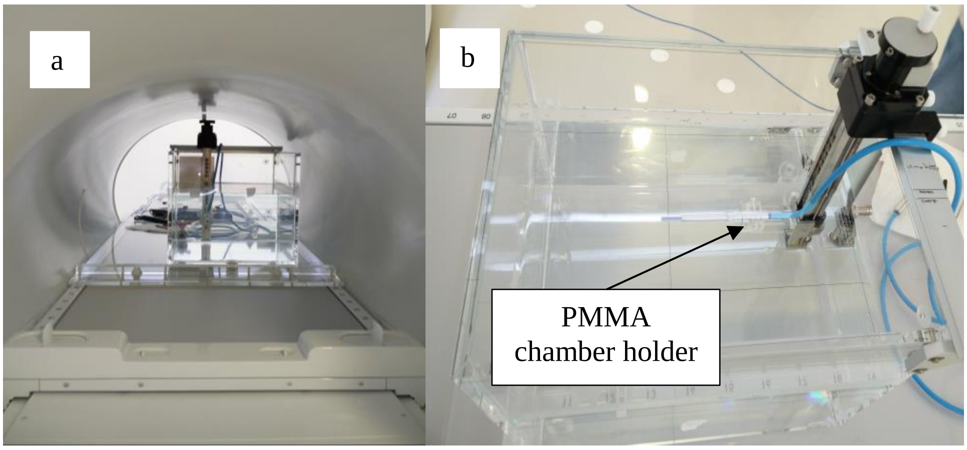

Figure 1: a) water tank setup in the bore of the MRI scanner and b) PMMA holder for a PTW Farmer-type chamber.

The PTW MP1 1D manual water phantom (MR-compatible) was used for the measurements. A polymethyl methacrylate (PMMA) holder that could accommodate the detectors was fixed to a manual stepping mechanism enabling the crossline movement. All measurements were performed with the chamber axis orientated perpendicular to the radiation beam and parallel to the B-field.

2.2 BEAM OUTPUT

Output measurements were performed using alanine dosimeters in the same water tank, as explained above, at a water-equivalent depth of 10 cm (the geometric centre of the measuring detector was set up at a depth of 10 cm from the front surface). The radiation beam was orientated either vertically or horizontally, the B-field was along the central axis of the bore and the water tank was positioned such that the longitudinal axis of the alanine detector was perpendicular to the beam and parallel to the B-field.

Following local practice, the water tank and the ionisation chambers were set up at the machine iso-centre. The iso-centre was defined based on the central pixel (iso-pixel) of 2D MV planar images using an electronic portal imaging device. Images were acquired with the gantry angle being 0° and 90°. The chamber cavity was aligned so that the iso-pixel, in images from both gantry angles, is shown at the centre of the cavity. The water tank was aligned and located so that the reference point of the detector would coincide with the indicated iso-centre.

Ambient air pressure was measured in the control room and temperature was measured with a mercury thermometer placed in the water tank.

The field size was defined by the leaves of the multi-leaf collimator (MLC) and was nominally 10 cm x 10 cm at the iso-centre. The ionisation chamber measurements were with beam deliveries of 200 MU, and alanine measurements were with beam deliveries of 2250 MU on the 1^{st} and 2^{nd} visit and 2038 MU on the 3^{rd} visit.

2.3 ION RECOMBINATION

An ionisation chamber reading must have a correction applied for the incomplete collection of charge due to ion recombination, k_{ion}. By assuming that the ion recombination is less than 3%, the two voltage method (equation 1) is a good approximation to determine k_{ion}. So, ion recombination is defined as:

$$k_{ion} - 1 = \frac{(\mathrm{M}_1/\mathrm{M}_2) - 1}{(\mathrm{V}_1/\mathrm{V}_2) - 1} \qquad (1)$$

where M_1 and M_2 are the collected charges at the polarising voltages V_1 and V_2, respectively. Ion recombination for the different chamber types were determined from measurements using the water tank.

2.4 $\mathrm{TPR}_{20/10}$ MEASUREMENT

A Tissue Phantom Ratio ($\mathrm{TPR}_{20/10}$) measurement was performed using a water-proof Farmer-type chamber (type 30013, s/n: 03981).

The ionisation chamber collected charge in a beam delivery of 200 MU at a fixed source-to-chamber distance. The thickness of water in front of the chamber was either 10 cm or 20 cm and the ratio of readings at each depth was taken.

2.5 DOSE AS A FUNCTION OF POSITION FOR ALANINE

The dose per MU delivered to each alanine pellet in a Farmer-type holder was investigated as a function of position within the holder.

2.6 MAGNETIC FIELD CORRECTION FACTOR

The B-field correction factor, k_Q^B, corrects for the effects of the difference between the reference condition (no B-field) and the actual user condition (with B-field). For the determination of k_Q^B we could use the analogy of the beam quality correction factor, k_{Q,Q_0}. This is explained further in this section.
The reference measurement of the absorbed dose is determined by the detector's response, M, and the application of the calibration coefficient in terms of absorbed dose to water, $N_{D,w}$, under the reference conditions used in the standards laboratory.

$$\mathrm{D_w} = \mathrm{M}\ \mathrm{N_{D,w}}$$

In most clinical situations the measurement conditions do not match the reference conditions used at the standards laboratories. Usually, dosimeters are used in a different energy beam from that used at a standards laboratory (which is typically ^{60}Co). In order to measure the dose to water in the user beam quality, Q, the effect of the difference between the reference beam quality Q_0 and the actual user quality Q needs to be corrected for. This can be achieved by applying a beam quality correction factor ($\mathrm{k}_{\mathrm{Q,Q_0}}$).

$$D_{w,Q} = M_Q\, k_{Q,Q_0}\, N_{D,w,Q_0}$$

The correction factor k_{Q,Q_0} is defined as the ratio of the calibration coefficient that you want, $N_{D,w,Q}$, divided by the calibration coefficient that you have, N_{D,w,Q_0}.

$$k_{Q,Q_0} \equiv \frac{N_{D,w,Q}}{N_{D,w,Q_0}}$$

Similarly, the B-field correction factor, k_Q^B, is defined as the ratio of the calibration coefficient that you want, $N_{D,w,Q}^B$, divided by the calibration coefficient that you have, $N_{D,w,Q}$.

$$k_Q^B \equiv \frac{N_{D,w,Q}^B}{N_{D,w,Q}}$$

The absorbed dose to water, measured under the influence of a particular B-field, is the product of the measured signal from the detector used in that B-field and the detector's calibration coefficient for that B-field (which can be determined at a primary standards laboratory).

$$D_{w,Q}^B = M_Q^B\, N_{D,w,Q}^B$$

However, if the calibration coefficient is applicable to a B-field of 0 T, then k_Q^B could be used to determine the absorbed dose to water for B-fields greater than 0 T.

$$D_{w,Q}^B = M_Q^B\, k_Q^B\, N_{D,w,Q}$$

In the current work, alanine dosimetry was used as a reference detector to determine $N_{D,w,Q}^B$ for a variety of ion chambers in the MR-linac (Billas I. *et al.*, 2017).

3 RESULTS

3.1 $TPR_{20/10}$ MEASUREMENT

A $TPR_{20/10}$ was determined using the water-proof Farmer-type ionisation chamber (type 30013, s/n: 03981). The values were found to be:

- 1st visit 0.697
- 2nd visit 0.696
- 3rd visit 0.700

3.2 MR-LINAC BEAM OUTPUT

Alanine dosimeters were used to calibrate the MR-linac output (determined in cGy/MU) over the three visits. The dose per alanine pellet was read out using EPR spectroscopy on return to NPL and a B-field correction factor was applied to get the absorbed dose to water at 1.5 T B-field strength. Table 1 shows results of the MR-linac beam output at each day per visit and the average of all days per visit. In the same table, the standard deviation of the mean (SDOM) is also presented. SDOM is defined as:

$$\mathrm{SDOM}\ (\%) = \frac{\sigma_{n-1}}{\bar{x} \cdot \sqrt{n}} \cdot 100$$

Where:
σ_{n-1} is the standard deviation of n readings

x̅ is the mean of n readings and
n is the number of readings

Table 1. The MR-linac output as measured using alanine dosimeters over three visits.

	1st visit (0 T)		2nd visit (1.5 T)		3rd visit (0 T)	
	Average (cGy/MU)	SDOM (%)	Average (cGy/MU)	SDOM (%)	Average (cGy/MU)	SDOM (%)
Day 1	-	-	0.871	0.18	0.986	0.20
Day 2	0.888	0.09	0.875	0.39	0.988	0.19
All days	0.888	0.09	0.873	0.21	0.987	0.13

3.3 MR-LINAC REPEATABILITY

The stability of the MR-linac and the setup repeatability are presented in figure 2, which shows the signal of the field detector (PTW Farmer chamber, s/n: 03981) over the period of 2 days on the 2nd visit (figure 2.a) and 3rd visit (figure 2.b). The statistical analysis is shown in table 2.

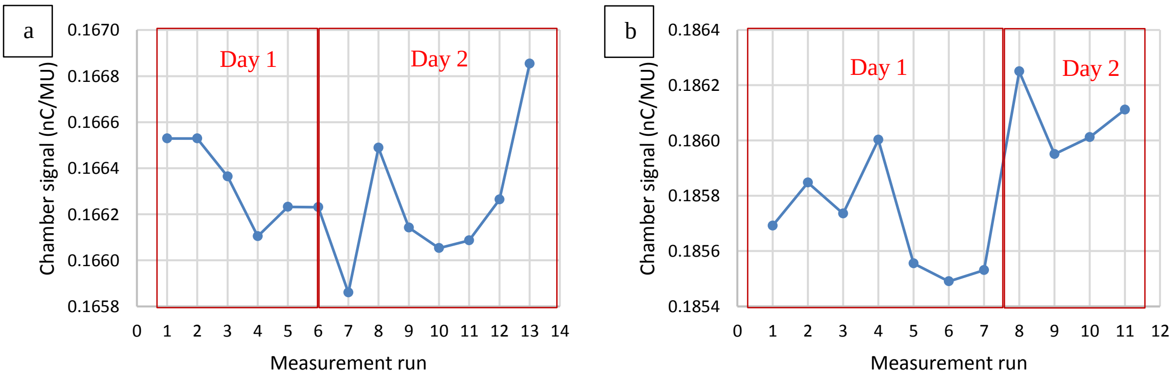

Figure 2: Chamber signal in nC/MU over 2 days for a) the 2nd visit and b) the 3rd visit.

Table 2. Statistical analysis of MR-linac stability and setup repeatability.

	2nd visit		**3rd visit**	
	Average nC/MU	SDOM (%)	Average nC/MU	SDOM (%)
Day 1	0.1664	0.05	0.1857	0.10
Day 2	0.1662	0.06	0.1861	0.07
All days	0.1663*	0.04	0.1858*	0.14

* Weighted average

3.4 ION RECOMBINATION

Table 3 shows the ion recombination (measured at the MR-linac) of the three ionisation chambers for 0 T and 1.5 T.

Table 3. Ion recombination of three ionisation chambers

Chamber type and serial number	k_{ion}	
	0 T	1.5 T
PTW Farmer-type (s/n 03981)	1.0050	1.0048
PTW Farmer-type (s/n 09145)	1.0038	1.0036
IBA Farmer-type (s/n 3520)	1.0063	1.0056

3.5 CALIBRATION BY SUBSTITUTION

The alanine measurements from the MR-linac at RMH were used to calibrate each of the ionisation chambers by the method of substitution.

Ionisation chamber calibration coefficients (Gy/C) in terms of absorbed dose to water derived from measurements performed at the MR-linac at RMH are shown in tables 4, 5 and 6 for the 1st, 2nd and 3rd visit, respectively. Alanine pellets were used as reference detectors and were corrected for the effect of the B-field at 1.5 T (correction of 0.996). The calibration coefficients were obtained as the ratio of dose to water measured using alanine and the corrected chamber reading. The results are relative to the MR-linac monitor chamber for a beam delivery of 200 MU.

Table 4. Summary of ionisation chamber calibration coefficients (Gy/C) in terms of absorbed dose to water as measured in the MR-linac at RMH. **1st visit (0 T)**

Chamber type and s/n	$N_{D,w,Q}$
PTW Farmer-type (s/n 03981)	5.293E+07
PTW Farmer-type (s/n 09145)	5.229E+07

Table 5. Summary of ionisation chamber calibration coefficients (Gy/C) in terms of absorbed dose to water as measured in the MR-linac at RMH. **2nd visit (1.5 T)**

Chamber type and s/n	$N^B_{D,w,Q}$ (Day 1)	$N^B_{D,w,Q}$ (Day 2)	$N^B_{D,w,Q}$ (Weighted average)
PTW Farmer-type (s/n 03981)	5.232E+07	5.256E+07	5.247E+07
PTW Farmer-type (s/n 09145)	5.197E+07	5.198E+07	5.198E+07
IBA Farmer-type(s/n 3520)	4.700E+07	4.716E+07	4.712E+07

Table 6. Summary of ionisation chamber calibration coefficients (Gy/C) in terms of absorbed dose to water as measured in the MR-linac at RMH. **3rd visit (0 T)**

Chamber type and s/n	$N_{D,w,Q}$ (Day 1)	$N_{D,w,Q}$ (Day 2)	$N_{D,w,Q}$ (Weighted average)
PTW Farmer-type (s/n 03981)	5.307E+07	5.303E+07	5.306E+07
PTW Farmer-type (s/n 09145)	5.252E+07	5.263E+07	5.257E+07
IBA Farmer-type(s/n 3520)	4.724E+07	4.733E+07	4.728E+07

3.6 DOSE DELIVERED TO ALANINE AS A FUNCTION OF POSITION

The dose delivered to each alanine pellet in the Farmer-type (F-type) holder was measured at NPL. The pellets were labelled 1 – 5, with 1 being closest to the stem of the alanine holder. Figures 3.a, 3.b and 3.c show results of the MR-linac output for each individual pellet in cGy/MU for the 1st, 2nd and 3rd visit, respectively. Each line represents the five readouts from the stack of pellets in one holder. Red lines indicate the 1st day of measurements and black dashed lines indicate the 2nd day of measurements. Except 3.a, where measurements were only performed on one day.

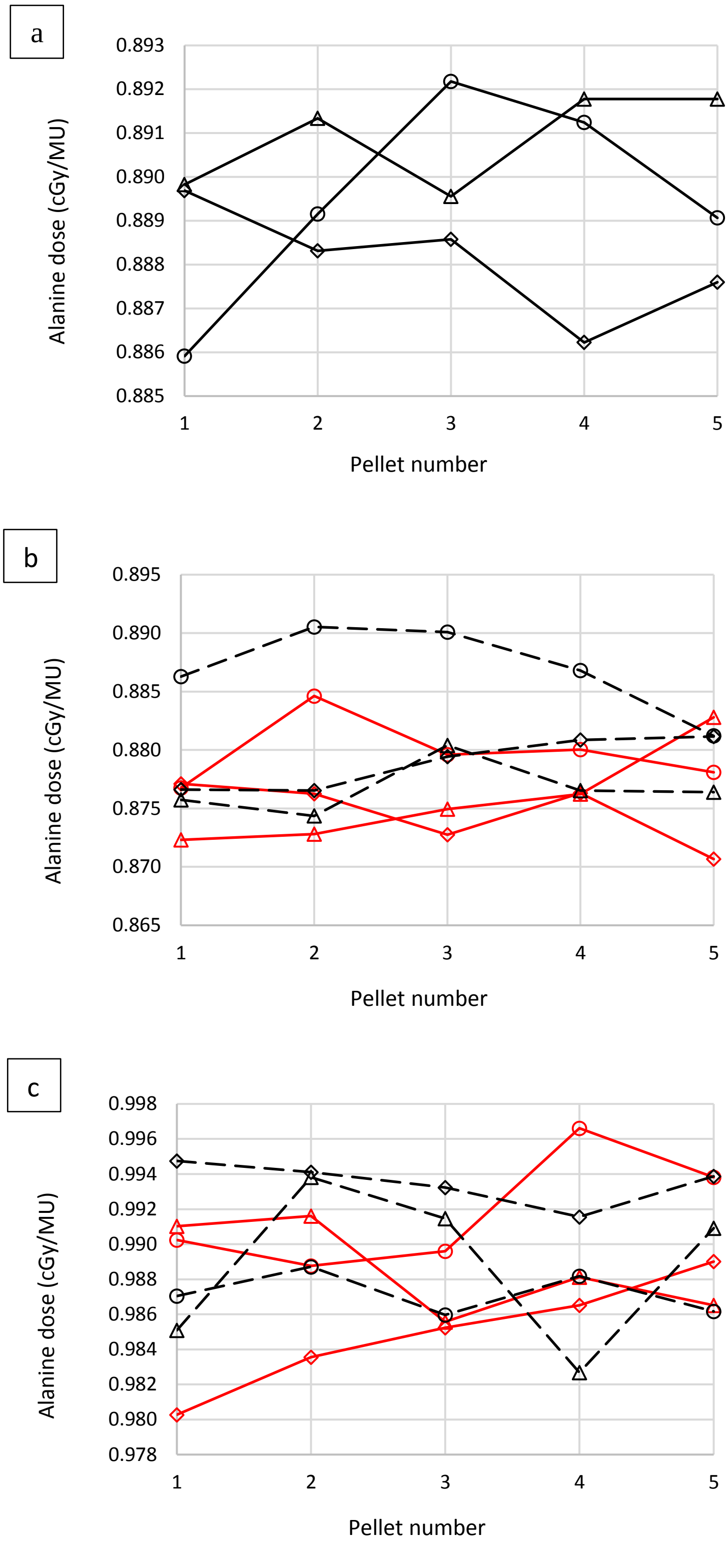

Figure 3: Alanine dose, in terms of cGy/MU as a function of alanine pellet position within an F-type holder. Each line represents the five readouts from one holder. Red lines and black dashed lines indicate the 1st and the 2nd day of measurements, respectively. a) 1st visit, b) 2nd visit and c) 3rd visit.

4 DISCUSSION

The MR-linac beam output was calibrated using alanine dosimetry at each day and it was determined in terms of cGy/MU as described in section 3.2. The maximum spread of the beam output calibration determined with alanine pellets was found to range between 0.3% and 1.4%.

The MR-linac stability over a period of 2 days was examined in this work. It was found that there was a maximum spread of 0.4%, with no trend on the data.

Ion recombination at 0 T and 1.5 T B-field strength for all chambers was determined. The values at 1.5 T were found to be lower for all chambers. However, this difference is within the uncertainties of the ion recombination (evaluated to be 0.04%).

A summary of the ionisation chamber calibration coefficients (Gy/C) in terms of absorbed dose to water as measured in the MR-linac was presented. Calibration coefficients were relative to the machine monitor unit (MU) and the maximum spread over two days for all chambers was found to range from 0.3% to 0.8%.

The variation in dose from pellet to pellet within the F-type alanine holder appears to be consistent. No systematic trend was observed and the maximum variation was found to be ±0.1 Gy.

The B-field correction factor, k_Q^B, can be determined based on the method described in section 2.6 and the results of section 3.5.

The uncertainty in the absorbed dose to water calibration coefficients, N_{Dw}, determined based on the alanine measurements at the MR-linac at RMH, is 2%. The uncertainty is based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a coverage probability of approximately 95%.

5 CONCLUSION

It is possible to carry out accurate dosimetry in the MR-linac beam at RMH, Sutton, provided care is taken in the setup and positioning of any phantom used.

Calibration coefficients for different ionisation chambers were determined using alanine dosimetry as a reference standard with an uncertainty of 2% ($k = 2$).

In order to complete reference dosimetry measurements using ionisation chambers (provided that the ionisation chamber is calibrated in a zero B-field), a correction is required for the effect of the B-field strength. It is possible to calculate this correction by using either the calibration coefficients determined directly at the MR-linac or indirectly using alanine as a reference detector.

6 ACKNOWLEDGEMENTS

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