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**REPORT ON DOSE MEASUREMENTS ON THE ELEKTA UNITY
MR-LINAC AT CHRISTIE HOSPITAL PERFORMED BY NPL**

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Report on dose measurements on the MR-linac at Christie Hospital performed by NPL

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Chemical Medical and Enviro Science

ABSTRACT

This report describes measurements of the radiation dose from the MR-linac at Christie Hospital 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 constant magnetic field (1.5 T) of the MR-linac 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 on 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 dosimeter's signal. Although the photon beam is not affected by the B-field, the direction of motion of the secondary electrons is changed (known as the 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 ($\parallel$) or perpendicular ($\perp$), 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:

- ($\perp$) to the B-field and the radiation beam is ($\perp$) to B-field, the change is ranging from 4% - 11.3%.
- ($\parallel$) to the B-field and the radiation beam is ($\perp$) to B-field, the change is <1%.
- ($\parallel$) or ($\perp$) to the B-field and the radiation beam is ($\parallel$) 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.

2 PURPOSE

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 Christie Hospital, Manchester. The measurements involved determining beam output as well as calibration coefficients, by substitution, for each of the ionisation chambers.

Two different routes of achieving traceability to existing primary standards will be examined: one directly to an MR-linac through ion-chambers (traceable to the VSL primary standard water calorimeter) and the second through a conventional linac through alanine detectors (traceable to the NPL primary standard graphite calorimeter).

Three of the ion chambers used have previously been calibrated using VSL's primary standard water calorimeter in the Elekta MR-linac at UMC-U, and these chambers serve as a transfer standard in this work, providing traceability to the VSL primary standard.

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 MRI-linac has a small effect on the sensitivity of alanine in terms of absorbed dose to water (Billas *et al.*, 2018). 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 is mostly dominated from the effect of the B-field on absorbed dose to water. This correction was determined by interpolating the MR-linac beam quality (at Christie) 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 and the Farmer-type ionisation chambers on table 1, 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 traceable to the NPL reference standard of absorbed dose to water.

Table 1. Farmer-type ionisation chambers calibrated at NPL in a conventional Elekta Synergy linac

Ionisation chamber	Type	Serial number	NPL certificate reference
PTW	TW30013	03981	2018RD0103981-1
PTW	TW30013	009923	2018RD01009923-1
IBA	FC65-G	3520	2018RD013520-1
IBA	FC65-G	3821	2018RD013821-1
PTW	TW30013	9486	2018RD01009486-1
PTW	TW30013	9487	2018RD01009487-1
PTW	TW30013	9145	2018RD01009145-1

The results from the current report, will give for each ionisation chamber used the:

1. Calibration coefficients traceable to MR-linac through ionisation chamber.
2. Calibration coefficients traceable to conventional linac through alanine dosimetry (for 1.5 T B-field strength).
3. Determination of the magnetic field correction factor, k_Q^B , for detectors calibrated in the conventional linac at NPL.
4. Machine calibration using the VSL's transfer standards and the NPL's alanine dosimetry.

Three national measurements institutes participated in this investigation (NPL, VSL and PTB) and two hospitals (RMH and Christie).

3 MATERIAL AND METHODS

Measurements were made in the MR-linac facility at Christie (18 to 21 September 2017) and in a conventional linac at NPL (zero B-field strength). Measurements at NPL include calibration of Farmer-type chambers, in a range of different beam qualities, listed on table 1. For information regarding

the calibration process, refer to the NPL certificates of calibration of ionisation chamber in terms of absorbed dose to water (reference for the certificate of each chamber is provided on table 1).

Results are presented for days between 19 and 20 September 2017.

Absorbed dose was measured per MU:

- at the iso-centre
- in a static horizontal beam (gantry angle = 90°), with the detector axis perpendicular to the beam and either parallel or perpendicular to the B-field
- in a field size of 10 cm x 10 cm at the measurement plane
- in a bespoke water tank (constructed at NPL)
- 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 Farmer-type chamber (type FC65-G)
- Alanine (five off 5 mm diameter and 2.5 mm thick pellets in a waterproof Farmer-shaped polyether ether ketone (PEEK) holder)
- Gafchromic EBT-3 film
- Monitor chamber: IBA waterproof Farmer-type chamber (type FC65-G)

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

3.1 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).



Figure 1: Measurement setup. Water tank placed on top of the table couch.

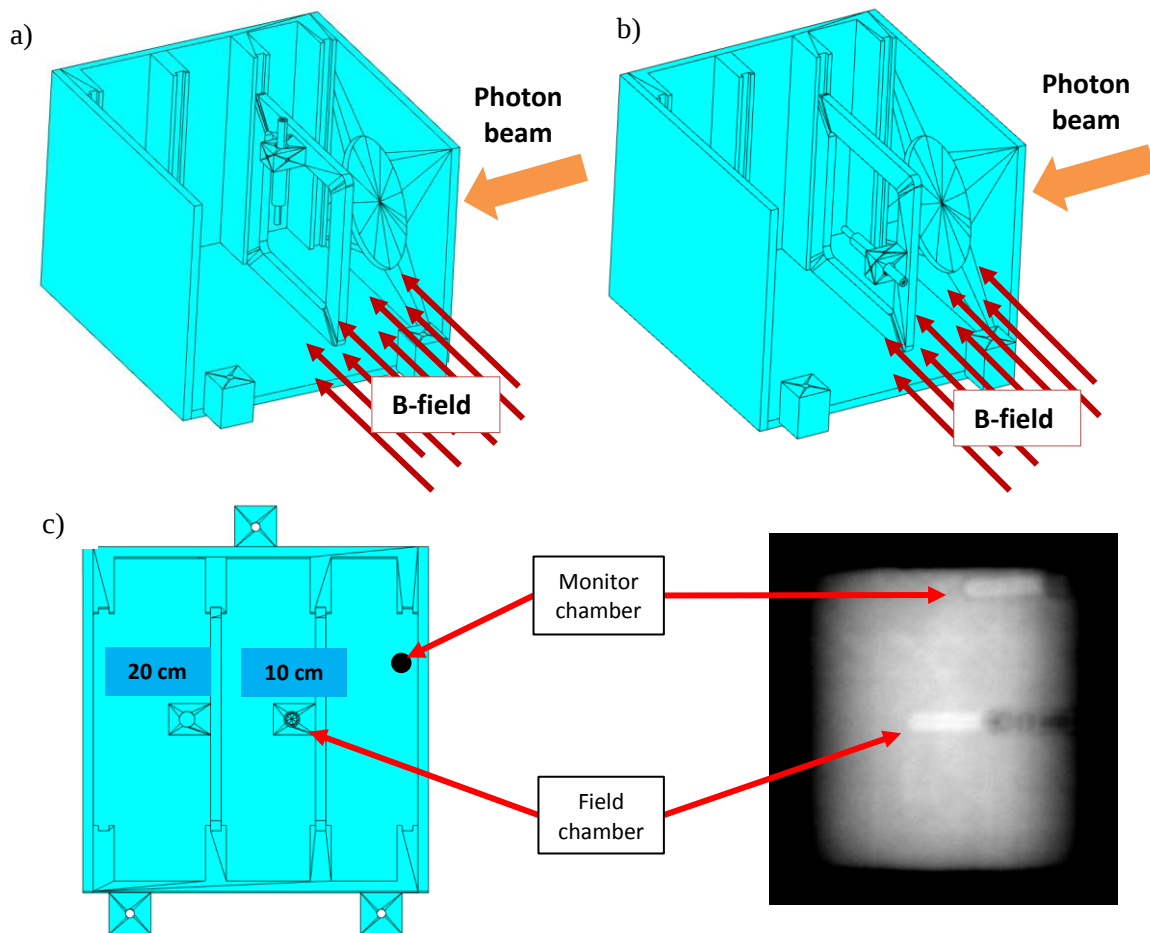


Figure 2: Water tank setup with the chamber axis orientated perpendicular to radiation beam and either a) perpendicular or b) parallel to B-field. The position of the monitor chamber is shown on c).

The water tank was built at NPL and has dimensions of 33 cm width, 33 cm length and 21.5 cm height. A square frame was constructed such that the chamber axis could be orientated either parallel figure 2.b or perpendicular figure 2.a to B-field, by a manual rotation of the frame by 90°, and maintaining the same chamber reference point. In both orientations, the chamber axis was always perpendicular to the radiation beam. Beam output was monitored by using a chamber placed inside the front of the water tank, in the corner of the primary beam (figure 2.c).

3.2 BEAM OUTPUT

Output measurements were performed using alanine dosimeters and the VSL's transfer standards 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 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 detectors was perpendicular to the beam and either parallel or perpendicular 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°. 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 2000 MU.

3.3 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:

$$k_{ion} - 1 = \frac{(M_1/M_2) - 1}{(V_1/V_2) - 1} \quad (1)$$

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.

3.4 TPR_{20/10} MEASUREMENT

A Tissue Phantom Ratio (TPR_{20/10}) measurement was performed using a water-proof Farmer-type chamber (30013/s/n: 03981) with chamber orientated perpendicular to B-field. 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.

3.5 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.

3.6 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.

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

In most clinical situations the measurement conditions do not match the reference conditions used at the standards laboratory. 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 (k_{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).

4 RESULTS

4.1 RADIATION BEAM CHARACTERISATION

A Gafchromic EBT-3 film was irradiated at the measurement plane. Film was processed and analysed based on the method described by Bouchard *et al.* (2009). Figure 3.a and figure 3.b shows the crossline (along the bore) and inline (across the bore) profile of the radiation beam, respectively.

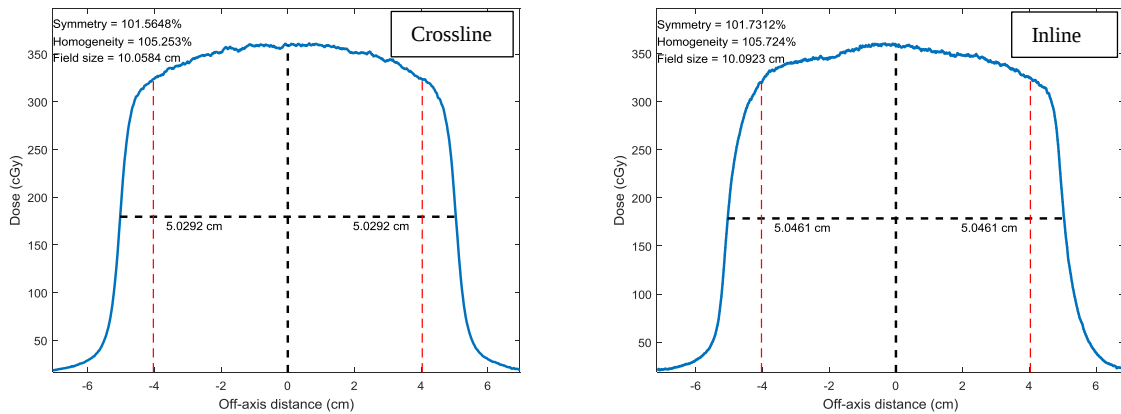


Figure 3: Crossline and inline profiles of the MR-linac radiation beam.

4.2 DOSE DELIVERED TO ALANINE AS A FUNCTION OF POSITION

The dose delivered to each alanine pellet in the F-type holder was measured at NPL. The pellets were labelled 1 – 5, with 1 being closest to the stem of the alanine holder. Figure 4.a shows results of the MR-linac output for each individual pellet in cGy/MU when the alanine holder was orientated

perpendicular (red lines) and parallel (blue lines) to the B-field. Each line represent the readouts from five alanine pellets in one holder.

A significant difference was found in the alanine signal between these two orientations, which we attribute to the air gap located between the stem and pellets (figure 4.b). Particularly, a difference in dose of approximately 10% was found between the first (closest to the stem) and the last (closest to the tip) pellet of the alanine F-type holder. The air gap arises because the holder was, unintentionally, not completely filled with pellets.

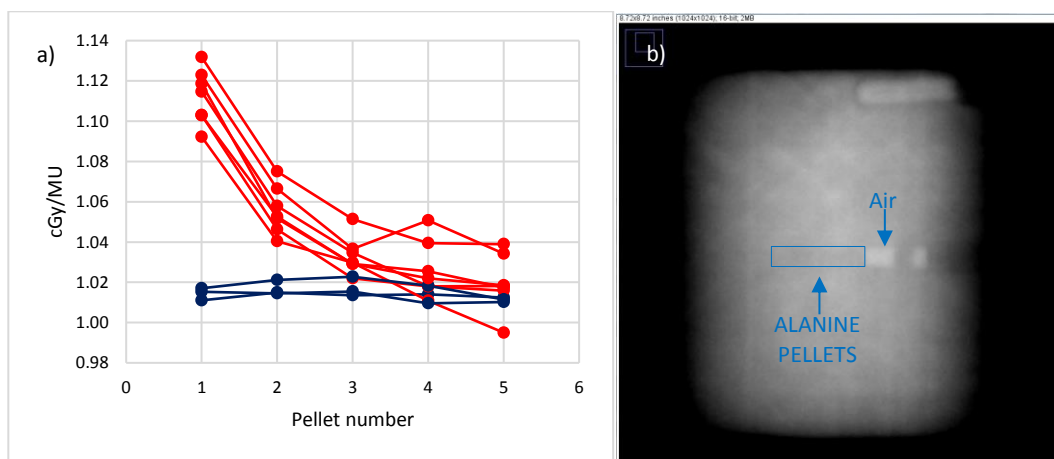


Figure 4: a) Alanine dose, in terms of cGy/MU as a function of alanine pellet position within the F-type holder. Each line represent the five readout from one holder when is orientated perpendicular (red lines) and parallel (blue lines) to the B-field. b) iView image showing the air-gap between the stem and alanine pellets.

In a previous investigation into the effect of parallel and perpendicular orientation of the alanine relative to the magnetic field direction, using an electromagnet in NPL's Co-60 facility orientation to B-field (figure 5), no effect was found, as shown in figure 6. To minimise the effects of the air gap therefore, the measurements made with alanine in the perpendicular orientation are excluded from further consideration in this report.

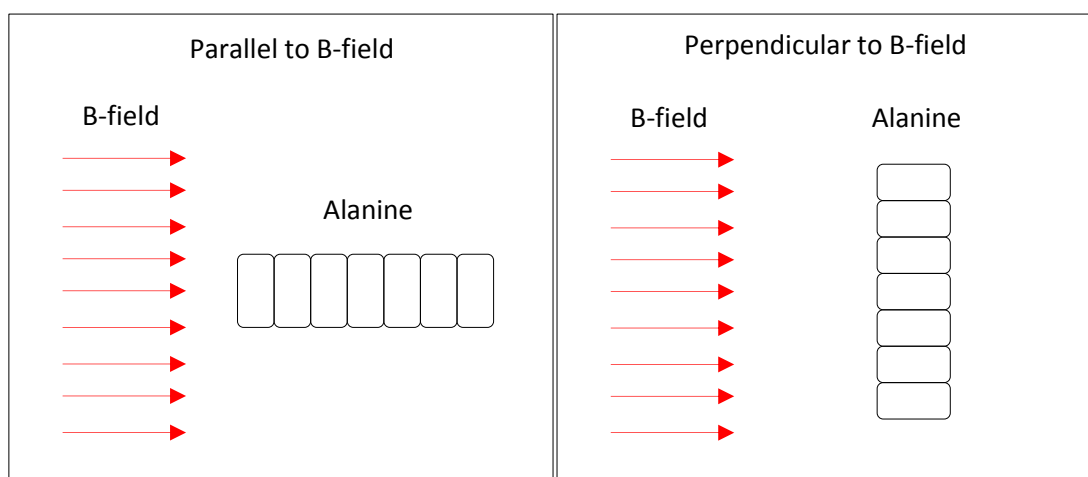


Figure 5: Alanine irradiation at NPL's electromagnet in parallel and perpendicular orientation to B-field.

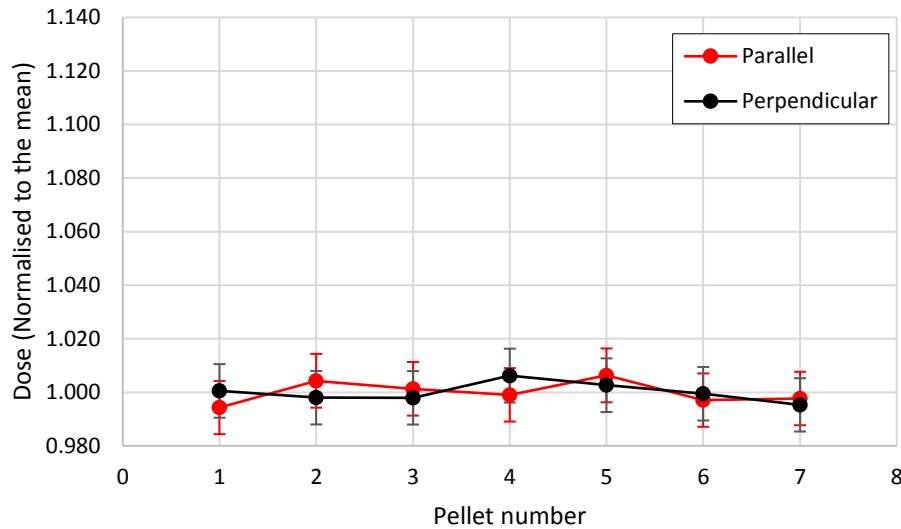


Figure 6: Normalised dose measured at NPL in Co-60 when alanine is irradiated parallel and perpendicular to B-field.

4.3 TPR_{20/10} MEASUREMENT

A TPR_{20/10} was determined using the water-proof Farmer-type ionisation chamber (type 30013, s/n: 03981). The value was found to be 0.700.

4.4 MRI-LINAC BEAM OUTPUT

The three transfer standard chambers and the alanine dosimeters were used to calibrate the MR-linac output (determined in Gy/MU) over the three days. Figure 7.a shows the average absorbed dose measured over the three transfer standards over the three days. Figure 7.b compare the consistency of traceability to VSL and to NPL, with the variability from day to day, when chamber axis is oriented perpendicular and parallel to B-field (average of the two orientations).

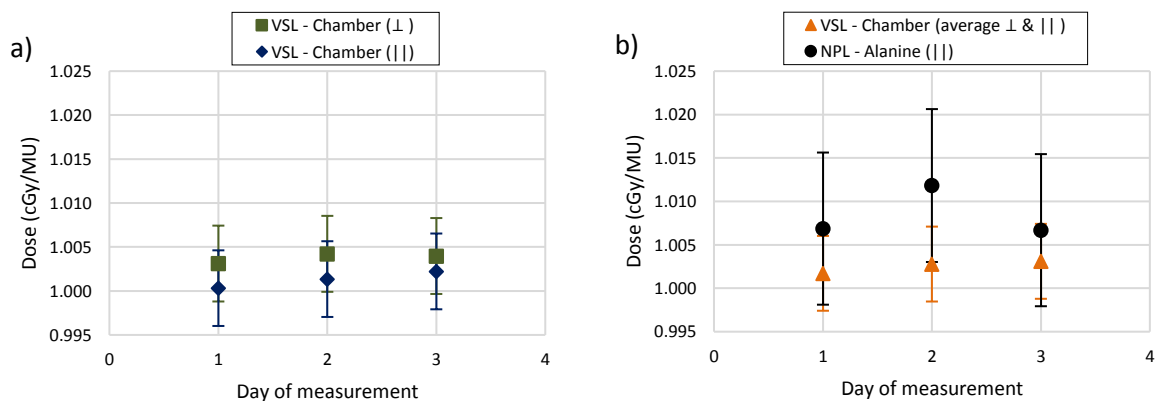


Figure 7: a) average absorbed dose measured over the three transfer standards over the three days. b) comparison between dose output measured using VSL's transfer standards and NPL's alanine by averaging perpendicular and parallel orientation data of chamber axis to B-field.

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 2 shows results of the MR-linac beam output, averaged over all days and as measured using the transfer standard and alanine, when the detector's axis is orientated either parallel or perpendicular to B-field. In the same table, the standard deviation of the mean (SDOM) is also presented. SDOM is defined as:

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

Where:

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

$\bar{x}$ is the mean of n readings and

n is the number of readings

Table 2. The MR-linac output (cGy/MU) as measured using the three transfer standards over three days.

NMI/Type/SN	Average of all days			
	Detector axis $\perp$ to B-field		Detector axis $\parallel$ to B-field	
	cGy/MU	SDOM (%)	cGy/MU	SDOM (%)
VSL/IBA/3213	1.004	0.03	1.002	0.03
VSL/PTW/7120	1.003	0.03	1.001	0.05
VSL/PTW/8377	1.005	0.06	1.000	0.05
NPL/Alanine	-	-	1.008	0.17

4.5 MRI-LINAC REPEATABILITY

The stability of the MR-linac and the setup repeatability are presented in figure 8, which shows the signal of the field detector (PTW Farmer chamber, s/n: 3213) for the parallel orientation of the chamber axis to B-field over the period of three days. The statistical analysis is shown in table 3.

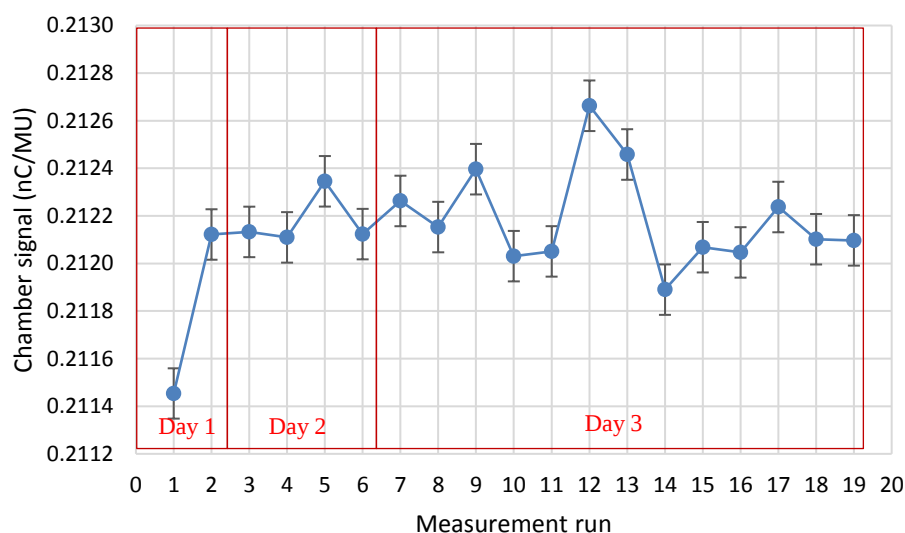


Figure 8: Chamber signal in nC/MU over 3 days.

Table 3. Statistical analysis of MR-linac stability and setup repeatability.

	Average nC/MU	SDOM (%)
Day 1	0.2118	-
Day 2	0.2122	0.03
Day 3	0.2122	0.05
All days*	0.2222	0.03

* Weighted average

4.6 ION RECOMBINATION

The ion recombination of two different type of ionisation chambers was measured for two different type of chambers and found to be:

- PTW waterproof Farmer-type (30013): 1.0040
- IBA waterproof Famer-type (FC65-G): 1.0048

4.7 CALIBRATION BY SUBSTITUTION

The VSL's transfer standards and the NPL's alanine measurements from the MR-linac at Christie 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 are shown in table 4. Three different orientations of the chamber axis with respect to the B-field are presented: perpendicular ($\perp$), parallel ($\parallel$) chamber pointing out – towards the table and anti-parallel (a- $\parallel$) chamber pointing in – towards the bore. Alanine pellets, orientated parallel to B-field, 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 transfer standards and 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 5 presents the B-field correction factors, k_Q^B , for the chambers calibrated at NPL in a conventional linac (zero B-field), traceable to NPL primary standard through alanine dosimetry.

Table 4. Summary of ionisation chamber calibration coefficients (Gy/C) in terms of absorbed dose to water as measured in the MR-linac at Christie traceable to VSL and NPL primary standards through ionisation chamber and alanine detector, respectively.

Centre/Chamber type/SN	$N_{D,w,Q}^B$ traceable to VSL through ionisation chamber (Gy/C)			$N_{D,w,Q}^B$ traceable to NPL through alanine detector (Gy/C)		
	$\perp$	$\parallel$	a- $\parallel$	$\perp$	$\parallel$	a- $\parallel$
NPL/PTW/03981	5.100E+07	5.270E+07	5.271E+07	5.131E+07	5.303E+07	5.303E+07
Christie/PTW/9486	-	5.230E+07	5.232E+07	-	5.262E+07	5.264E+07
PTB/PTW/6762	5.076E+07	-	-	5.107E+07	-	-
Christie/PTW/9487	-	5.223E+07	5.218E+07	-	5.255E+07	5.249E+07
RMH/PTW/9145	-	-	5.200E+07	-	-	5.231E+07
PTB/IBA/3069	4.514E+07	-	-	4.541E+07	-	-
NPL/IBA/3520	4.497E+07	4.715E+07	4.708E+07	4.525E+07	4.744E+07	4.737E+07
NPL/IBA/3821	4.517E+07	4.729E+07	4.725E+07	4.543E+07	4.757E+07	4.752E+07
PTB/IBA/3068	4.515E+07	-	-	4.543E+07	-	-

Table 5. Summary of B-field correction factors, k_Q^B , for the chambers calibrated at NPL, in conventional linac (zero B-field), traceable NPL primary standard through alanine detector.

Centre/Chamber type/SN	k_Q^B traceable to NPL through alanine detector		
	$\perp$	$\parallel$	a- $\parallel$
NPL/PTW/03981	0.966	0.998	0.998
Christie/PTW/9486	-	0.998	0.998
Christie/PTW/9487	-	0.999	0.998
RMH/PTW/9145	-	-	0.992
NPL/IBA/3520	0.957	1.003	1.002
NPL/IBA/3821	0.957	1.002	1.001

5 DISCUSSION

The radiation beam size was found to be 10.06 cm x 10.09 cm, which agrees well with the actual field size.

A variation of approximately 10% across the stack of alanine pellets within the holder, was found when the holder was irradiated perpendicular to the B-field. This is attributed to the electron return effect in the air gap at the stem end of the stack, which was present because the holders were not fully loaded with pellets. This variation has not previously been seen when such an air gap was not present. Only the results from the parallel orientation of alanine were used in the work reported here. The variation in dose from pellet to pellet within the alanine holder (in parallel orientation to B-field) shows no systematic trend and the maximum variation was found to be ± 0.1 Gy which is consistent with the repeatability.

The MR-linac beam output was calibrated on each day using the transfer standards and alanine dosimetry, in terms of cGy/MU as described in section 3.4. The maximum spread of the beam output calibration determined with the transfer standard and alanine pellets was found to be 0.6% and 0.5%, respectively.

The MR-linac stability over a period of three days was examined in this work. It was found that there was a maximum spread of 0.6%, with no trend on the data.

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

The B-field correction factor, k_Q^B , was determined based on the method described in section 2.6 for the chamber calibrated in a conventional linac at NPL.

The uncertainty in the absorbed dose to water calibration coefficients, N_{Dw} , determined based on the transfer standards and the alanine measurements at the MR-linac at Christie, is 1% and 2%, respectively. Uncertainty is based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a coverage probability of approximately 95%.

A comparison between absorbed dose measurements using the transfer standard (traceably calibrated at VSL) and alanine/EPR (traceably calibrated at NPL) was found to agree within the uncertainties. The standard uncertainty on dose output was 0.42% for transfer standards and 0.87% for alanine detectors. The observed deviations from unity, of the ratios alanine/chamber, is partly accounted for by the degree of equivalence of the NPL and VSL primary standards: 0.14% (6MV) and 0.37% (10MV) [Key comparison BIPM.RI(I)-K6] (i.e. dose measured traceable to NPL is slightly higher than dose measured traceable to VSL, though the difference is well within the standard uncertainty on the difference).

6 CONCLUSION

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

Calibration coefficients for different ionisation chambers were determined using two different routes of existing primary standards: one directly to an MR-linac through ion-chambers and the second through a conventional linac through alanine detectors with an uncertainty of 1% and 2% ($k = 2$), respectively.

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 the calibration coefficient determined at MR-linac using alanine as a reference detector.

7 ACKNOWLEDGEMENTS

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