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Malcolm McEwen[1], Bryan Muir[1],
Eugene Yip[2], Patricia Oliver[2], Michael Reynolds[2],
Shima Tari[2], Tania Wood[2], Neil Johnson[2]

[1]National Research Council Canada, Ottawa, ON
[2]Cross Cancer Institute, Edmonton, AB

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1. Background

The National Research Council of Canada has, in recent years, been developing a capability for using alanine dosimeters to measure absorbed dose to water at therapy dose levels in Co-60 and MV photon beams (Mansour, 2018). The stated uncertainty in the calibration of a batch of alanine dosimeters irradiated, in a therapy-level Co-60 irradiator, is 0.5 % and the uncertainty in the determination of dose using such dosimeters in a clinical radiation beam is estimated to be less than 1 % for doses in the range 10 Gy to 100 Gy. Other researchers (e.g. Billas *et al*, 2018) have demonstrated the suitability of alanine as a dosimeter for use in magnetic fields, and therefore the NRC capability was applied to the linac-MR installed at the Cross Cancer Institute. The purpose of this investigation was to provide external validation of the dose measured by medical physicists at the centre using standard dosimetry protocols and ionization chambers.

2. Methodology

A calibration curve for a single batch of alanine dosimeters (Harwell batch BY616) was established through reference Co-60 irradiations in the NRC Gammabeam X200 therapy-level irradiator in April 2022. Alanine pellets were irradiated in the same geometry as in Zeng *et al* (2004) at the standard reference depth of 5 cm in a water phantom with a field size of 10 cm × 10 cm at the surface of the water phantom. The dose rate, as established by the NRC primary standard water calorimeter, was 1.0962 Gy/min on the reference date of 1-Jan-22. Irradiation times were varied to provide doses in the range 20 Gy to 500 Gy. The temperature of the water in the phantom was monitored throughout and this was taken to be the temperature of the alanine pellets for the purpose of applying the known temperature correction (Sharpe *et al*, 2009; Desrosiers *et al*, 2012).

A set of dosimeters from the same batch of alanine pellets was despatched to the Cross Cancer Institute mid-November 2022. The dosimeters were loaded into POM[1] (Delrin™) holders with the same external dimensions as a Farmer-type ionization chamber (as shown in Figure 1). The holder includes an O-ring so that the pellets are hermetically sealed and the holder can be placed directly in a water phantom. As well as the holders to be irradiated, three holders with pellets, were sent as controls. One holder contained blank pellets and the others contained pellets irradiated to approximately 15 Gy and 25 Gy respectively in the NRC Co-60 beam (irradiations carried out 9-Nov-22). By including these controls, the effect of the transport process on both un-irradiated and irradiated pellets could be assessed.

[1] Polyoxymethylene

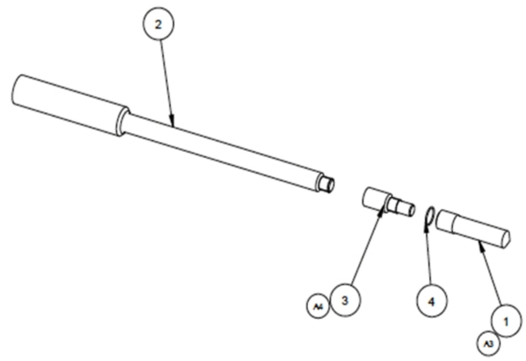

Figure 1. Drawing of holder for alanine pellets. The end capsule can hold six standard alanine pellets (5 mm diameter, ~3 mm thick). A single stem (part 2) is used for multiple holders.

The pellets were irradiated on 17th November 2022 (as reported by CCI staff) and then returned to the NRC for read-out. The pellets remained in their POM holders for the duration of the experiment – from loading at the NRC, through irradiation, to being returned to the NRC for read-out. This meant that any environmental effects (e.g., due to varying humidity) were minimized.

The linac-MR beam (nominally 6 MV) was calibrated as follows:

Reference chamber	Standard Imaging A12
Phantom	Water
Gantry	0°
Field size	10 cm × 10 cm
Reference depth	10 cm
Thimble alignment	Thimble Chamber long axis aligned to Sup-Inf Direction, Beam and B Field on Ant-Post direction. (Patient HFS)
Position verification	Mechanical (laser)
Protocol used	a) AAPM TG-51: Measured $TPR_{20,10}$ converted to $\%dd(10)_x$. $k_Q = 0.9968$ b) In House MC Simulations $k_B = 1.000$

The ion chamber readings were corrected for air density (P_{TP}) and the linac calibration was found to be 1 MU = 0.7333 cGy (as reported by CCI staff). After calibration, the alanine irradiations were carried out in both water and solid water phantoms. Rather than deliver a range of doses, all dosimeters were irradiated to the same dose of 15 Gy (nominal).

The irradiated alanine pellets were then read out using the NRC EPR spectrometer system (Bruker EMX with Xenon upgrade). There is always a waiting period between irradiation and read-out to allow for radical stabilization (24-48 hours for the NRC read-out protocol). All pellets were readout on the 5th December 2022 and the same read-out protocol was used throughout. The alanine signal was normalized to the mass of each pellet and also corrected to the NRC reference temperature of 21 °C (temperature coefficient used = - 0.14% per °C).

3. Results

3.1 NRC irradiations

The NRC Co-60 alanine calibration is shown in Figure 2. For doses up to 500 Gy there is a linear relationship between the alanine intensity and the delivered dose, although an increasing non-linearity is seen at higher dose levels. In addition to normalizing each pellet's EPR signal by its mass, a reference ruby artifact is used to monitor variations in the spectrometer system. The ruby is kept permanently positioned in the EPR cavity of the spectrometer, and the assumption is that any variation in the ruby EPR signal is directly correlated with a change in an alanine pellet signal. Although all doses for this investigation were below 50 Gy, the entire calibration curve was used as the high dose points robustly constrain the linear fit of the alanine dose response.

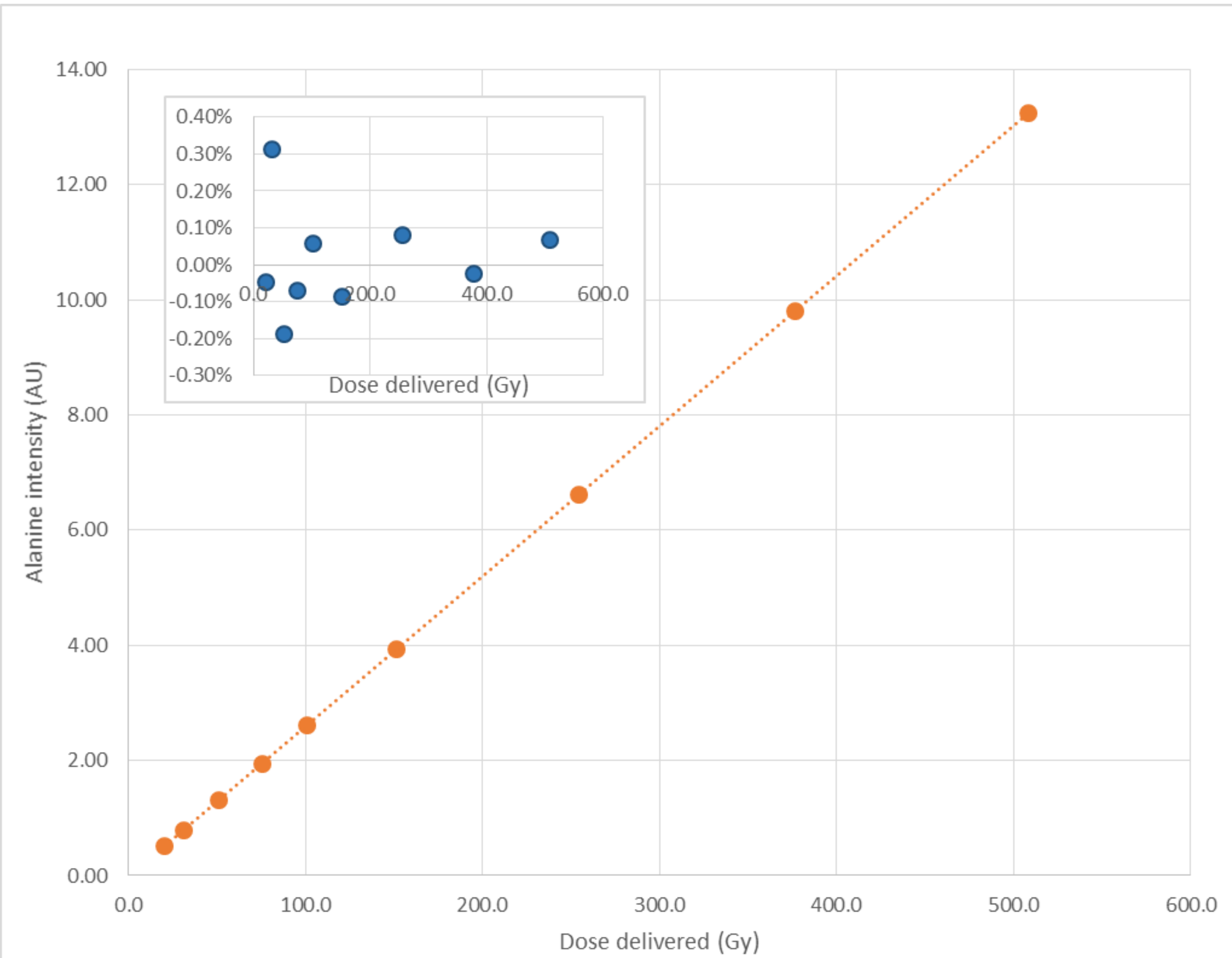

Figure 2. Calibration data for alanine batch, pellets irradiated at NRC. The inset plot shows the relative deviations of the linear fit, which are typically less than 0.2 %. The Type A standard uncertainty of the EPR signal of the five pellets in each irradiation was, on average, around 0.2%.

3.2 Cross Cancer Institute linac-MR irradiations

The data for the CCI irradiations are shown in Table 1.

Table 1 Summary of CCI linac-MR irradiations 17-Nov-2022

Irradiation label	*Phantom*	D_{stated} (Gy)	M_{read_corr} (Arb units)	Std unc [1]	D_{read} (Gy) [2]	Ratio (D_{read}/D_{stated})
1	Water	14.90	0.38386	0.2%	14.96	1.0041
2	Water	14.89	0.38720	0.1%	15.08	1.0127
3	Water	14.90	0.38643	0.1%	15.05	1.0107
4	SW[3]	14.83	0.38065	0.2%	14.83	0.9999
5	SW	14.84	0.38091	0.3%	14.84	1.0005
6	SW	14.84	0.37902	0.2%	14.77	0.9956
B[4]		24.99	0.64700	0.3%	25.00	1.0001
C		15.00	0.38618	0.1%	15.00	0.9999
D		24.99	0.64932	0.2%	25.08	1.0036

[1] This is the Type A uncertainty k=1) only, obtained from the five pellets read from each holder

[2] Based on the Co-60 calibration, corrected for reported energy dependence of alanine and the effect of a 0.5 T magnetic field

[3] The specific type of solid water was Gammex RMI. Backscatter thickness beyond position of alanine dosimeters was ~ 5 cm.

[4] Letters refer to dosimeters irradiated at NRC in the Co-60 beam. “C” and “D” were mailed with the other holders, “B” was irradiated at the same time as “C” and “D” and stored at NRC.

The uncertainty of the NRC measurements of the alanine dosimeters irradiated at the CCI are summarized in Table 2. This uncertainty budget is based on that constructed by Mansour (2018) and is significantly less than the standard uncertainty quoted for OSLD and RPLD audit services offered by other organizations.

Table 2. Uncertainty budget for NRC measurements of alanine dosimeters irradiated in the CCI linac-MR beam in terms of absorbed dose to water

Component of uncertainty	**Standard uncertainty (%)**
Realization of dose (primary standard)	0.4
Signal measurement – calibration	0.18
Temperature @ calibration	0.05
Mass of pellet	0.05
Spectrometer reproducibility	0.25
Calibration fit	0.35
Signal measurement – irradiation	0.20
Energy dependence correction factor	0.25
Magnetic field correction factor	0.2
Temperature @ irradiation†	0.1
Transportation of dosimeters¶	0.21
Combined standard uncertainty (k=1)	**0.76**

† Temperature at irradiation was supplied by CCI staff, an uncertainty of 0.3 °C is assumed.

¶ Takes into account possible signal variation (e.g. due environmental effects or free radical recombination)

4. Discussion

The three control irradiations give agreement between the measured and stated doses, within the Type A uncertainties and therefore no transport correction to D_{read} for the dosimeters irradiated in the linac-MR beam is required.

Using a Co-60 calibration for the alanine (zero magnetic field) means that two corrections are required, one for the relative energy response of alanine and one for the effect of the 0.5 T magnetic field. The former has been investigated by many authors and is summarized well by Anton *et al* (2013). For a photon energy in the range 6-8 MV, a correction factor of 1.005 is appropriate (i.e., the apparent dose determined from a Co-60 calibration should be multiplied by 1.005). The magnetic field correction has been investigated by Billas *et al* (2018) and data from that publication was analyzed to give a correction factor for a 0.5 T field of 0.998 (i.e., the apparent dose determined from a Co-60 calibration should be multiplied by 0.998).

The results in Table 1 can be combined to give a mean values for measurements in both water and solid water in Table 3.

Table 3. Summary of alanine irradiations

Phantom	Mean dose (Gy)	Std dev[1]	D_{read}/D_{stated}
Water	14.89	0.5 %	1.0092
Solid Water	14.83	0.3 %	0.9986

[1] The standard deviation of the distribution of mean dose values should be consistent with the standard uncertainty on the dose measurement for a single irradiation (Table 1) for the data to be considered as a single set.

There is an apparent difference of 1 % between measurements in water and in solid water, but it is not possible to conclude that this is statistically significant, given the uncertainties. Combining the uncertainty budget in Table 2 with the data given in the TG-51 Appendix (McEwen *et al*, 2014) and removing the common component of the Canadian primary standard of absorbed dose to water, then it is clear that the level of agreement between stated and measured doses is within the overall k=1 uncertainty. Other than the common primary standard, the two dose measurement methods use different reference data and rely on significantly different physical bases for the raw measurement and read-out. This independence does result in an overall larger standard uncertainty (due to an increased number of factors involved compared to a comparison of ion chamber measurements) but it also provides increased confidence in the end-to-end process.

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