Characteristics of a compact tabletop alanine EPR dosimetry system

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Purpose

The large, specialized equipment necessary for contemporary electron paramagnetic resonance (EPR) prohibits many institutions from utilizing alanine dosimetry. Micro-EPR systems may provide a mechanism for routine alanine dosimetry but several questions remain about their response characteristics across a wide dose range that reflect their viability as a useful dosimeter outside the manufacturer-stated accuracy and thus was the focus of this study.

Alanine EPR background

Alanine is an alpha-amino acid that is a promising dosimeter due to its near-tissue equivalence, stability, and linear dose response. When purified, the crystalline form of alanine can be fabricated into pellet dosimeters. The signal measured with alanine is fundamentally related to tissue damage by the ionizing radiation that induces two primary free radicals species [1, 2], which are detectable using an EPR spectrometer such as the one shown in Figure 1.

Figure 1: Magnettech MiniScope MS 5000X microEPR spectrometer studied in this work [3].

Spectral Analysis

EPR measures the first derivative of the free radical abundance within a sample [4]. The EPR spectral signature of the sample is dependent on the incident microwave power and field modulation width used to measure the spectra, Figure 2.

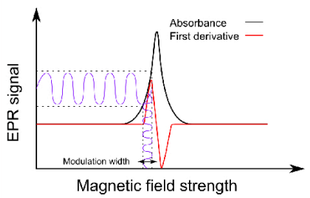

Figure 2: A simple EPR system spectra and illustration of field modulation.

Alanine EPR spectra were acquired using a Magnettech MiniScope MS 5000X spectrometer, Figure 1, and subtracted from a daily characterized background signal, corrected for any linear thermal trends in the resonator cavity, and quantified by the ratio of spectral amplitudes between the alanine and a stable, well-known ruby, Figure 3.

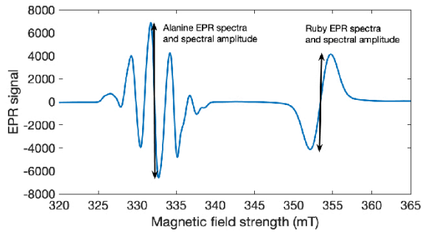

Figure 3: A 1 kGy alanine and reference ruby EPR spectra. Dose is proportional to the ratio of the spectral amplitudes.

EPR scanning parameter

Optimization of field modulation width and microwave power parameters, which are plotted in Figure 4:

- Maximize signal SNR between the alanine sample and reference ruby
- Measurements performed using a high-signal 1 kGy pellet
  - Modulation widths evaluated from 0.05 mT to 1.0 mT
  - Microwave power evaluated from 1 mW to 50 mW
- Alanine and noise floor increased proportionally with modulation
  - Ruby saturated near 0.6 mT
- Ruby and noise floor increased proportionally with microwave power
  - Alanine saturated near 16 mW
- Optimal scanning parameters set to 0.55 mT modulation width and 6.2 mW microwave power

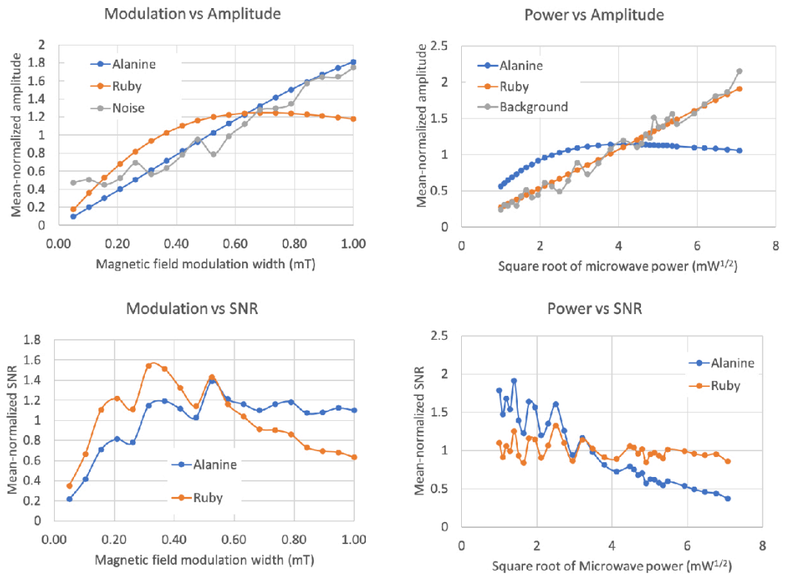

Figure 4: Measured dependencies of magnetic field modulation width and microwave power on spectral amplitude and SNR. Response curves have each been normalized to their respective means.

Dose response linearity

- Pellets were irradiated with a 6 MV beam quality to known doses across decades of 1.0 Gy, 10 Gy and 100 Gy dose to water, which are plotted in Figure 5.
- Each measurement consisted of four EPR scans among four dosimeters
- Linear regression was performed in MALTAB across each decade
- An Analysis of Covariance (ANACOVA) was performed among fits and are summarized in Table 1
  - Statistical significance tests were performed among each calibration curve's slope
  - The response of the alanine-EPR system changed significantly between different dose ranges
- Fit residuals used to estimate error in fit unique to each calibration range

Table 1: Linearly regressed parameters and the root-mean-squared error across each decade of dose response. The largest p-value when comparing fit uniqueness among the other decades is listed for each fit.

Dose range	Slope (Gymg/EPR)	Dose offset (Gy)	RMS residual (%)	Slope p-value significance
1-10 Gy	2.157E4	-0.077	0.81	0.003
10-100 Gy	2.094E4	-0.271	0.32	0.043
100-1000 Gy	2.115E4	-0.230	0.30	0.023

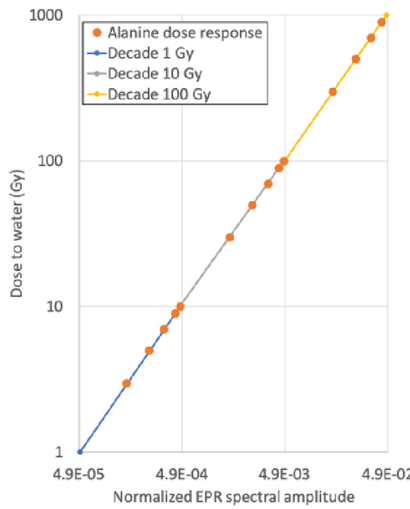

Figure 5: Dose response curves plotted for each decade of dose response. Linear fits are listed in Table 1.

System sensitivity and variability

Measurement uncertainties were characterized by EPR stability, pellet variability, and measurement-analysis variability. Uncertainties in the dose-to-water are estimated for each dose decade reflective with changes in the EPR signal amplitude. These estimates reflect sources of uncertainty from the determination of a calibration curve and measurement variability and are listed in Table 2.

Table 2: Summary of EPR variability and measurement uncertainties.

Component	$k = 1$ confidence	Type
Dwell position reproducibility	0.66	B
Ruby stability	0.05	B
Inter-scan repeatability, 10 Gy	1.15	A
Inter-scan repeatability, 100 Gy	0.07	A
Angular variability	0.30	A
Orientation difference	0.25	A
Inter-pellet variability	0.28	A
Post-irradiation stability	0.04	B
Inter-person variability	0.14	B
Fit residual error, 1 - 10 Gy	0.82	B
Fit residual error, 10 - 100 Gy	0.04	B
Fit residual error, 100 - 1000 Gy	0.003	B

- Repeatability reflects random variations in the EPR spectra
- Stability of the ruby was characterized from several repeated measurements relative to a 1 kGy reference pellet
- Dwell reproducibility was assessed from the sensitivity profile measured for the resonator cavity
- Inter-person variability was quantified among four people repeating EPR measurements of identical alanine pellets

Conclusion and Future Work

This work demonstrates the basic characterization of a compact EPR system to be used for alanine dosimetry, which includes the optimization of scanning parameters and dose response linearity. Several aspects of measurement repeatability and reproducibility were also investigated. Further work will aim to develop post-anlaysis methods to improve measurement precision and comprehensively evaluate dose-to-water measurement uncertainties.

References

1. E. Sagstuen, Phys. Chem., 1997
2. M. Heydari, Phys. Chem., 2002
3. Magnettech, MiniScope Manual
4. A. Gago-Arias, Inst., 10, 2015

Acknowledgements

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