ALANINE DOSIMETRY AT NPL — THE DEVELOPMENT OF A MAILED REFERENCE DOSIMETRY SERVICE AT RADIOTHERAPY DOSE LEVELS

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Abstract

In this paper we describe the work that has been carried out at National Physical Laboratory (NPL) to develop a mailed alanine reference dosimetry service for radiotherapy dose levels. The service is based on alanine / paraffin wax dosimeters produced at NPL. Using a data analysis technique based on spectrum fitting, it has been possible to achieve a precision of dose measurement better than ±0.05 Gy (1σ). A phantom set has been developed for use in high energy photon beams, which enables simultaneous irradiation of alanine dosimeters and ionisation chambers in a well defined geometry. Studies in photon beams of energies between ^{60}Co and 20 MeV have shown no significant energy dependence (<1%) for alanine relative to dose determination using a graphite calorimeter. Work is underway to extend the service to electron beams, and preliminary results are presented on the direct calibration of alanine in electron beams using a graphite calorimeter.

1. INTRODUCTION

The potential of alanine as a dosimeter for radiotherapy applications has been appreciated for many years, but it is only recently that developments in instrumental and analytical techniques have enabled reliable measurements to be made at doses between 1 and 10 Gy. Alanine dosimeters are

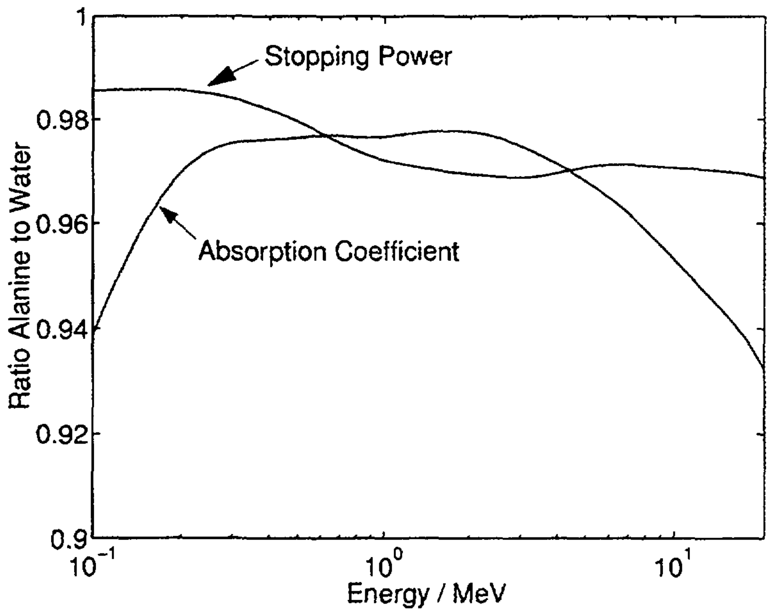

FIG. 1. Ratio of alanine mass energy absorption coefficients and mass collision stopping powers to those of water, as a function of energy.

intrinsically close to water both in terms of density and radiation absorption properties. Figure 1 shows the ratio of mass collision stopping powers and mass energy absorption coefficients for alanine and water. Mass collision stopping power ratios vary only slowly with energy, changing by approximately 2% over the energy range 0.1 to 20 MeV, shown in Fig. 1. Mass energy absorption coefficient ratios show more variation with energy, and the ratio alanine to water falls rapidly below 0.1 MeV. Nevertheless, in the region between 0.2 and 10 MeV, variation is relatively small, and the ratios themselves are close to the ratios of stopping powers. This suggests that the alanine dosimeter should show only small energy dependence in the high energy photon region used for radiotherapy. It should be noted that the variation in response of alanine with energy will also be influenced by variation in the radiation chemical yield, and this can only be determined by experiment.

NPL has operated an alanine mailed reference dosimetry service in the 0.1 to 70 kGy region since 1991, and the work described in this paper represents the extension of that service to the radiotherapy dose region.

2. DOSIMETERS

Alanine dosimetry at NPL is based around NPL produced pellets comprising, by weight, 90% L-α-alanine and 10% high melting point paraffin wax (m.p. 98°C). The pellets are 5 mm diameter and approximately 2.5 mm thick. The average mass varies slightly from batch to batch, but is nominally 55 mg. Pellets are selected to be within a ±2 mg band. Each pellet is weighed immediately prior to measurement, and the EPR signal normalised for mass by simple division. The production process has been described earlier [1], and does not introduce any detectable alanine radical signal (see later). In order to reduce post-irradiation fading, dosimeters are conditioned at 55% relative humidity for 10 weeks prior to use. An NPL alanine dosimeter consists of four pellets enclosed in either a polyacetal or polystyrene holder. Two types of holder are used: a cylinder of outer diameter 12 mm and height of 17 mm, in which the pellets are stacked on top of each other, and a disc of diameter 25 mm and thickness 6 mm, in which the pellets lie side by side. The cylindrical holder can be made water tight for use in a water phantom. The four pellets in a dosimeter are measured separately. Above 10 Gy individual pellet doses are calculated, but below 10 Gy it is necessary to sum the signals from individual pellets to achieve the required precision. All data described in this paper are based on summed signals from four pellets.

3. SPECTROMETER PARAMETERS

Microwave power, modulation amplitude and spectral acquisition time can all be increased in an attempt to detect smaller signals, and hence measure lower doses. None of these is without penalty, and a compromise has to be made in order to record relatively undistorted spectra in a reasonable time. The use of excessive microwave power or modulation amplitude can also lead to machine instability. Details of the spectrometer and measurement parameters used at NPL are given below:

Spectrometer - Bruker ESP 300, X-band with 9" magnet;
Cavity - standard Bruker st4102 rectangular cavity;
Microwave power - 6 mW;
Modulation amplitude - 0.6 mT;
Field sweep - 20 mT;
Acquisition time - 120 s (6 x 20 s scan with 90° rotation of pellet between 3rd and 4th scan).

Reproducible positioning of the sample and associated holder within the EPR cavity is essential for high accuracy at any dose. Experience at NPL indicates that this becomes more critical at low doses, where spectrometer baseline distortions are comparable in amplitude to the radical signal being measured. To ensure reproducible positioning a sample holder has been designed based on two concentric quartz tubes. This holder also allows automatic rotation of the pellet through 90°, in order to average out anisotropic effects. This holder has been described in detail previously [2], but for completeness, is shown schematically in Fig 2. An automatic pellet loading system based around this holder has also been developed [3].

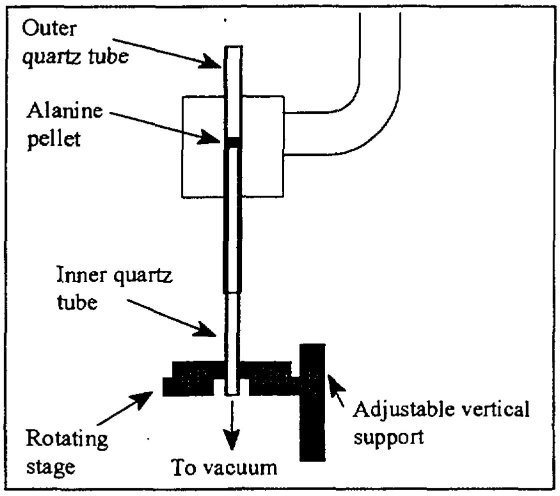

FIG. 2. Schematic diagram of system for holding alanine pellets in EPR cavity.

4. DATA ANALYSIS

The most common method of analysis of alanine/EPR dosimeters is the measurement of the peak-to-peak height of the central feature of the radiation induced radical spectrum. This works well at doses above approximately 10 Gy, and has been shown to be superior to supposedly more sophisticated methods, such as double integration [4]. Below 10 Gy, the measured EPR spectrum becomes increasingly affected by both high frequency noise, and low frequency baseline distortion. The high frequency noise component can be removed by filtering, but the low frequency distortion is more problematic. Baseline distortion can arise from several sources, including, the cavity, the holder used to position the alanine, and the alanine sample itself. Much of this distortion can be removed by subtracting the average spectrum of unirradiated pellets from the spectrum of an irradiated one. There remains, however, a significant component that varies from pellet to pellet and cannot be removed by simple subtraction. In order to take account of this, we have developed a procedure based on Least Squares techniques, which allows estimation of the amount of the "known alanine radical spectrum" that is present in the distorted measured signal. The "known alanine radical spectrum" is determined by measuring the spectrum of a pellet irradiated to 100 Gy. All spectrometer parameters, except signal channel gain, are the same as those used for measurements below 10 Gy. The procedure used has been described previously [2], and is illustrated in Fig. 3, where a measured 5 Gy spectrum a) is shown split into its component parts. Spectrum b) is the average baseline spectrum obtained by measuring a number of unirradiated pellets, and c) is the computed "dosimeter dependent" part of the spectrum, which is approximated by a fourth order polynomial function. Spectrum d) shows the amount of the underlying "known alanine radical spectrum" that is present in the measured signal.

5. ACHIEVABLE ACCURACY AND PRECISION

Using the data analysis procedure described above, the relationship between the amount of the "known alanine radical spectrum" and absorbed dose is found to be linear over the range 1 to 10 Gy, with no significant "zero dose" intercept. Measurement precision, as determined by the residual standard deviation about the line, is better than ±0.05 Gy (1σ). This translates into a minimum usable dose of 5 Gy for a reference dosimetry service, assuming a realistic requirement of 1% (1σ) for the precision of a single measurement.

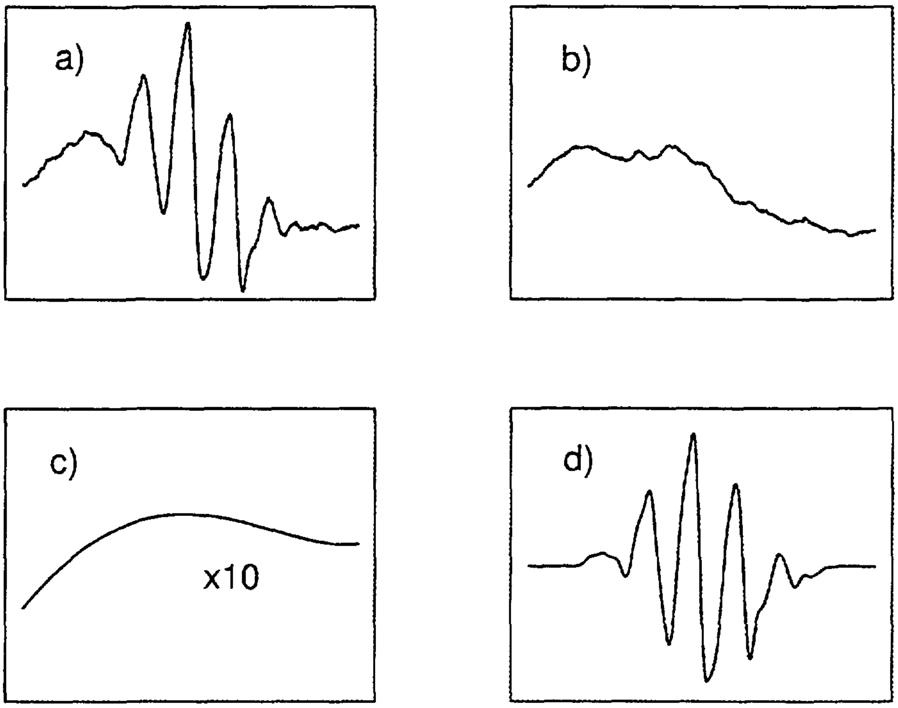

FIG. 3. Analysis of EPR spectrum in terms of its component parts: a) Measured EPR spectrum of alanine dosimeter irradiated to 5 Gy. b) Average baseline of unirradiated dosimeters. c) Calculated polynomial correction for individual dosimeter baseline. d) Calculated component of known alanine radical spectrum. The y-scale of plot c) is expanded 10 times relative to that of the other plots.

Overall accuracy depends on a number of factors, including, the calibration standard being used and the accuracy of correction for factors such as energy dependence, irradiation temperature and post-irradiation fading. In radiotherapy applications, temperature can generally be monitored and controlled within quite tight limits, and uncertainties due to irradiation temperature effects are therefore usually negligible. Similarly, fading is not usually a significant problem, and can be monitored by the use of irradiated control dosimeters, which accompany the service dosimeters during transport. The rate of fade of NPL dosimeters stored at 55% R.H. has been measured to be approximately 4% over a 17 month period. NPL alanine dosimeters are calibrated in terms of absorbed dose to water using Co-60 radiation, in a field whose dose rate is directly traceable to the NPL primary standard graphite micro-calorimeter. The overall uncertainty associated with this calibration is estimated to be ±2% (2σ). Uncertainties arising from the energy dependence of the alanine dosimeter are discussed below.

6. PHANTOM

In radiotherapy calibration applications, it is essential that alanine dosimeters are irradiated under well defined conditions, and in such a way that their dose reading can be easily related to the dose reading of other systems, such as ionisation chambers. In order to achieve this with a mailed service, a polymethylmethacrylate (PMMA) phantom plate has been designed for photon irradiations, which enables alanine dosimeters in cylindrical holders (12 mm diameter, 17 mm length) to be irradiated alongside thimble ionisation chambers (either NE 2561 or NE 2571). The alanine and ionisation chamber inserts are interchangeable, allowing the two to be exchanged half-way through an irradiation, in order to eliminate the effect of field asymmetry. To achieve the standard measurement depths of 5 or 7 cm, additional, locally provided, phantom material is placed in front of and behind the 2 cm thick PMMA plate. The PMMA plate is shown in Fig. 4.

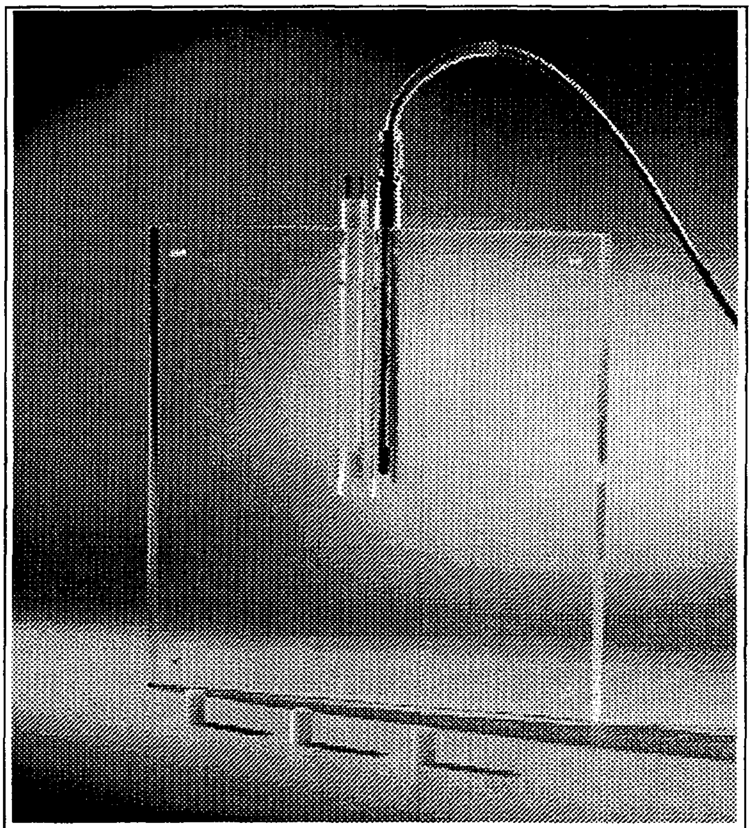

FIG. 4. Phantom plate showing interchangeable locations of ionisation chamber and alanine dosimeter.

7. PHOTON ENERGY DEPENDENCE

One of the most important potential applications for alanine at therapy level is as a reference dosimetry service for quality assurance and audit purposes. In order to minimise systematic errors, the response of dosimeters used for such applications should ideally have very little dependence on radiation type and quality. Figure 5 shows a plot of the relative response of NPL alanine dosimeters irradiated over a range of photon energies. Radiation quality is given in terms of Tissue Phantom Ratio ($TPR^{20}{}_{10}$), a measure of the effective energy of the photon beam. The range plotted corresponds to photons from Co-60 and those generated between 4 and 20 MeV. The basis of dose determination at each quality was the NPL graphite micro-calorimeter, the conversion to absorbed dose to water being made using the photon fluence scaling theorem [5]. As can be seen, there is no significant energy dependence over this energy range, all experimental points lying within a 1% band. Also shown in Fig. 5, for comparison, is the relative response of a NE 2561 ionisation chamber.

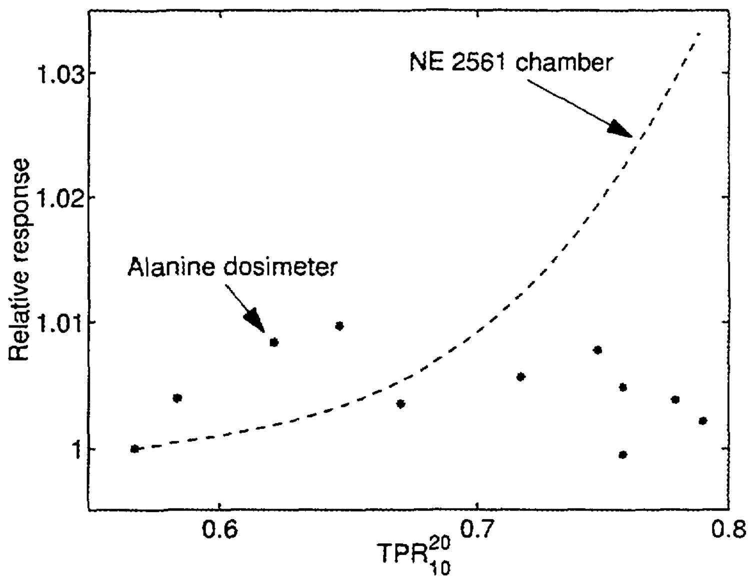

FIG. 5. Relative response of alanine dosimeters and ionisation chambers in high energy photon beams.

8. ELECTRON RESULTS

Work is currently underway at NPL to extend the therapy level alanine service to high energy electron beams. In order to provide a direct calibration of alanine in electron beams, a replica of the primary standard electron beam calorimeter has been constructed. This replica has cut-outs which allow four alanine pellets to be embedded directly in the calorimeter core. Three energies have been studied, nominally 6, 10 and 16 MeV. The absorbed dose to alanine was derived by multiplying the absorbed dose to graphite in the calorimeter core by the mean alanine to graphite stopping power ratio, calculated for the known spectrum of the NPL beam. As discussed above, alanine dosimeters are normally used with an absorbed dose to water calibration derived from the primary standard graphite micro-calorimeter in a Co-60 beam. This can be converted into an absorbed dose to alanine calibration using cavity theory, and compared directly with the electron beam derived calibration. Data analysis is not yet complete, but provisional results for the 10 MeV irradiations show agreement between the electron beam and Co-60 calibrations within 0.6%, (derived from 19 individual measurements, with a scatter of 0.6% (1σ)). This agreement is well within the uncertainties of the comparison, and demonstrates the equivalence of alanine response in Co-60 and high energy electron beams.

9. CONCLUSION

A mailed reference dosimetry system for high energy radiotherapy photon beams has been developed based on alanine/paraffin wax dosimeters. A limiting measurement precision of ±0.05 Gy has been shown to be consistently achievable using a Bruker ESP 300 spectrometer and standard rectangular cavity, provided steps are taken to ensure precise sample positioning. A data analysis procedure based on spectrum fitting has been developed to correct for dosimeter dependent baseline distortions. A phantom plate and adapter set has been designed to enable simultaneous irradiation of alanine dosimeters and ionisation chambers. No significant energy dependence (<1%) has been observed in photon beams from Co-60, or generated between 4 and 20 MeV. Provisional results from a 10 MeV electron beam also indicate no significant difference in response compared to Co-60.

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