Investigation of ultrasonic properties of MAGIC gels for pulse-echo gel dosimetry

T J Atkins¹², V F Humphrey², F A Duck¹ and M A Tooley¹

¹Department of Medical Physics and Bioengineering, Royal United Hospital, Combe Park, Bath BA1 3NG, UK

²Institute of Sound and Vibration Research, University of Southampton, Southampton, SO17 1BJ, UK

Email: timothy.atkins@nhs.net

Abstract. Ultrasound has been proposed as an alternative 3D method to read out dosimetric gels. The ultrasonic properties of MAGIC gel are investigated in relation to producing a dosimetry system based on a pulse-echo technique. The sound speed, attenuation coefficient, and density of MAGIC gel were measured over a range of temperatures and doses. A non-linear relationship between ultrasonic attenuation and dose was observed, with the attenuation below 10 Gy being approximately constant. The sound speed was 1550.3 ± 1.5 m s⁻¹ at 25 °C with a dose sensitivity of 0.14 ± 0.03 m s⁻¹ Gy⁻¹; both properties changed with temperature and were 1535.4 ± 0.8 m s⁻¹ and -0.08 ± 0.01 m s⁻¹ Gy⁻¹ respectively at 15 °C. The density also varied with temperature and dose, and was 1028.9 ± 0.3 kg m⁻³ with a dose sensitivity of 0.178 ± 0.004 kg m⁻³ Gy⁻¹ at 26 °C. The characteristic acoustic impedance of MAGIC gel was calculated to be 1.596 × 10⁶ kg m⁻² s⁻¹ at 0 Gy and 25 °C. The dose sensitivities measured indicate that changes to the characteristic acoustic impedance caused by irradiation are small, and therefore a reflector that has a similar characteristic acoustic impedance is required to maximise sensitivity of the pulse-echo technique. A suitable material has been developed and the reflection characteristics of the interface between MAGIC gel and the reflector are also temperature dependent. It is concluded that temperature management will be central to the development of any practical pulse-echo dosimetry system.

1. Introduction and background

Ultrasound has been proposed as a method of measuring the dose dependent changes induced by irradiation in polymer gels. Mather et al. [1,2] and Crescenti et al. [3] have both published data on the dose dependent changes that occur in polymer gels. Mather et al. proposed using time-of-flight tomography [2] to map radiation dose distributions, while Crescenti et al. [3] investigated the use of ultrasonic elastography. This paper records an investigation of the ultrasonic properties of a MAGIC gel as part of the development of a dosimeter based on the pulse-echo method of dose readout. The concept is to use a composite material, in which one constituent is more dose dependant than the other, resulting in scattering or reflections that are dose dependant and can be read with a conventional ultrasound scanner.

To produce an ultrasonic pulse-echo dosimetry system it is important to determine the characteristic acoustic impedance (Z) of the gel material, that is the product of the density (ρ) and...
speed of sound \( (c_0) \). The acoustic attenuation coefficient of the gel is also important as this will affect the received signal amplitude on which a pulse-echo dosimeter will be based. A pulse-echo readout system will require a component material that is not dose dependant; the acoustic properties for this material must also be determined.

2. Ultrasonic speed of sound and attenuation

For this study MAGIC gel, as developed by Fong et al. \cite{4}, was poured into specially constructed moulds of different thicknesses. A buffered insertion technique, with two 3.5 MHz transducers co-axially mounted in a temperature controlled water bath, was used to measure the ultrasonic speed of sound and attenuation coefficient.

2.1. Speed of sound

The speed of sound was measured at three different temperatures to determine the sensitivity of the ultrasonic properties to temperature. The measurements were performed by determining the time of flight of an ultrasound pulse through the samples with pure water being used as the reference medium. Measurements were made on three separate samples of different thicknesses (1, 2 and 3 cm) for each dose level; these were used to calculate the mean speed of sound and its standard deviation.

Figure 1 shows the variation in speed of sound with dose. The speed of sound for unirradiated gel decreased from 1550.3 ± 1.5 (1 S.D.) m s\(^{-1}\) at 25 °C to 1535.4 ± 0.8 m s\(^{-1}\) at 15 °C. The speed of sound appears to vary approximately linearly with dose over the range measured. At 25 °C the speed of sound increases with a dose sensitivity of 0.14 ± 0.03 m s\(^{-1}\) Gy\(^{-1}\), whereas at 15 °C the speed of sound decreases with dose, with a sensitivity of -0.08 ± 0.01 m s\(^{-1}\) Gy\(^{-1}\). The uncertainties in these slopes are quoted as 1 standard error obtained from the least-squares regression analysis.

![Figure 1. Variation in speed of sound of MAGIC gel with dose at three temperatures (see key). Error bars show the uncertainty (1 S.D.) calculated from the measurements for the different samples.](image)

2.2. Attenuation

Tone burst pulses were used to measure the attenuation coefficient. A range of frequencies was selected around the centre frequency of the transducers. Attenuation was measured using a buffered insertion technique. The attenuation coefficient was calculated from the gradient of the graph of
transmitted signal level as a function of thickness for three samples irradiated to the same dose. This technique removes the effect of window attenuation.

Figure 2 shows the variation of attenuation coefficient of MAGIC gels with dose at the discrete frequencies used for measurement. The measurements were made at a temperature of 25 °C. There appears to be little change in attenuation coefficient for each frequency below 10 Gy irradiated dose, whereas above 10 Gy the attenuation coefficient appears to increase with dose. The attenuation coefficient is greater for higher ultrasonic frequencies.

![Figure 2. Attenuation coefficient measured at discrete frequencies (see key) for MAGIC gel irradiated to different doses at 25 °C. Error bars show the uncertainty (1 standard error) calculated from regression analysis.](image)

3. Density

To determine the dose dependency of the density of MAGIC gel, some gel was poured into flexible-walled sachets. The sachets were irradiated to a range of doses from 0 to 30 Gy. Subsequently the densities of the MAGIC gel sachets were measured at 3 different temperatures. Calculation of the densities was based on measurements of the mass of the samples and the volume of fluid displaced by the samples when they were immersed in water.

Figure 3 shows the variation in density with dose. The density of unirradiated MAGIC gel increased from 1028.9 ± 0.3 kg m\(^{-3}\) at 26 °C to 1033.3 ± 0.3 kg m\(^{-3}\) at 14.5 °C. The density increases linearly with dose over the range measured with a dose sensitivity of 0.178 ± 0.004 kg m\(^{-3}\) Gy\(^{-1}\).
Figure 3. Variation of density of MAGIC gel with dose for three different temperatures (see key).

4. Acoustic reflector
The measurements of density and speed of sound can be used to calculate the characteristic acoustic impedance of MAGIC gel \((Z = \rho \cdot c_0)\) and how this changes with radiation dose. The characteristic acoustic impedance is calculated to be \(1.596 \times 10^6\) \(\text{kg m}^{-2} \text{s}^{-1}\) at 0 Gy and 25 °C, while it is \(1.586 \times 10^6\) \(\text{kg m}^{-2} \text{s}^{-1}\) at 15 °C. The dose sensitivities measured indicate that changes to the characteristic acoustic impedance caused by irradiation are small. The dose sensitivity over the range of temperatures measured increases from \(193\) \(\text{kg m}^{-2} \text{s}^{-1} \text{Gy}^{-1}\) at 15 °C to \(424\) \(\text{kg m}^{-2} \text{s}^{-1} \text{Gy}^{-1}\) at 25 °C. To produce an acoustic reflection that is sensitive to these small changes in acoustic impedance requires a reflector with a similar acoustic impedance to accentuate the relative change in impedance.

A polymeric material has been developed with an acoustic impedance matched to the MAGIC gel. Figure 4 shows the measured variation in reflection amplitude of an interface between the acoustic reflector and MAGIC gel averaged over regions irradiated to 0, 10, 20 and 30 Gy as a function of temperature. Each dose follows a similar pattern: starting at the lowest temperature, the reflected amplitude falls to a minimum and then increases as the temperature of the sample rises. The temperature at which the minimum occurs increases with irradiated dose. At this temperature the acoustic matching between the gel and backing is optimum. This suggests that in order to produce a practical pulse-echo dosimetry system based on this acoustic reflector a suitable temperature would need to be identified at which the reflection amplitudes showed the greatest proportional change over the dose range of interest.
Figure 4. Temperature and dose dependence of measured acoustic reflection amplitude for doses between 0 and 30 Gy (see key).

5. Conclusions
Selected acoustic properties of MAGIC gel have been determined by measurements with the intention of producing an ultrasound backscatter based gel dosimetry system. The variation in the acoustic properties with dose and temperature have been investigated and reported. These show for the first time the variation in sound speed with temperature, and density with dose and temperature. Also the sign of the gradient of the dose dependency of sound speed changes with temperature. The density increases linearly with dose, and the gradient of this dose dependency is invariant with temperature. A material for use as a backscatterer has been developed and the acoustic reflection amplitude from a plane surface of this material has been investigated for temperature and dose response. The reflection coefficient goes through a minimum at a dose-specific temperature; the temperature at which this minimum occurs increases with dose.

The variation in the acoustic properties with temperature indicate that temperature management will be central to the development of a successful pulse-echo dosimetry system. Any such system will require a temperature dependent calibration. To give maximum sensitivity a preferred temperature may be identified.

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