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An improved design for a stable and reproducible phantom material for use in near-infrared spectroscopy and imaging

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Abstract. In this note, we describe an improved phantom material for use in near-infrared spectroscopy and imaging. The material consists of a clear epoxy resin with absorbing dyes and amorphous silica spheres as scattering particles. It is possible to calculate the scattering coefficient and angular scattering distribution of the material from Mie theory, using the known size and refractive index of the silica spheres together with the measured refractive index of the resin (~ 1.56). We show a good agreement between prediction and experimental measurements. The scattering properties of the material closely match those of tissue in the near-infrared wavelength region, having an anisotropy factor, g, of approximately 0.93.

The absorption coefficient of the epoxy is low (~ 0.001 mm^{-1}), and addition of the dyes produces an absorption coefficient that covers the same range as that of tissue.

1. Background

Near-infrared (NIR) spectroscopy is currently being used widely to measure changes in the oxygenation of cerebral and other tissues in both neonates and adults (Wyatt *et al* 1986, Edwards *et al* 1988, Hampson and Piantadosi 1988, Peebles *et al* 1992, Elwell *et al* 1993, De Blasi *et al* 1993). There is also considerable interest in developing an imaging scheme using NIR spectroscopy to measure the oxygenation distribution in tissues, or as a screening technique for the detection of breast tumours (Grünbaum *et al* 1991, Key *et al* 1991, Barbour *et al* 1992, Schweiger *et al* 1993, Hebden and Delpy 1994). As part of these developments, there is a need for a stable and reproducible tissue-like phantom material, which can be used to investigate, in a controlled fashion, the propagation of NIR light through tissue.

In a previous paper (Firbank and Delpy 1993) we described a phantom material that could be used to approximate the scattering and absorption properties of tissue. This material, whilst useful, suffered from some limitations, both in its mechanical and its optical properties. Firstly, the material, which used titanium dioxide (TiO_2) particles to provide scattering, had rather isotropic scattering, with the mean cosine of its angular scattering distribution (g) being 0.5. This is significantly lower than that of most tissues, where g is typically > 0.9 (Cheong *et al* 1990). Secondly, using the polyester plastic described in the previous paper, we were forced to change our catalyst from methylethylketone peroxide (MEKP) to azoisobutyronitrile (AIBN). This was due to bleaching by the MEKP of many of the NIR absorbing dyes that were available for use with the polyester. AIBN does not have an effect on the dyes, but makes the casting procedure more complex, since it causes cracking to occur in single casts of over 100 g. This causes difficulty in preparing the large

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phantoms required for imaging work. Use of AIBN also seems to cause small refractive index fluctuations in the cured plastic (Firbank 1994). Finally, it was difficult to predict the scattering properties of the phantom, due to the broad (and ill determined) size distribution of the TiO_2 particles in the phantom, and because of the refractive index variations in the plastic. Ideally, we would want a material whose scattering properties could be predicted theoretically.

In this note we will describe an improved phantom based upon a different plastic together with different scattering particles. We show comparisons between the theoretically calculated and the measured optical properties.

2. Materials

The plastic used as a base for the phantoms is a two-part epoxy resin (MY753 resin with XD716 hardener, Ciba–Geigy Ltd). The epoxy sets to form an optically clear plastic which can be cast in blocks of up to 5 kg.

As a scattering material, we used amorphous silica spheres (Monospher 1000M, Merck Ltd). These have a well defined size distribution (1000 nm $\pm$ 10%) and a refractive index of 1.417 at 550 nm. The spheres have a surface coating of an methacrylate group, which aids dispersion in the epoxy resin. We are currently using the same dye as in our previous phantom (Pro Jet 900NP, Zeneca Ltd, Manchester, UK).

3. Phantom preparation procedure

First of all, separate stock suspensions of the dyes and scattering particles at high concentrations were made in the epoxy resin. Then, to make the phantoms, measured quantities of these suspensions were added to a mix of epoxy resin and hardener. The stock concentrated suspension of spheres in the resin (30% spheres by weight) was made by mixing together spheres and resin in a ball mill (model 9 ball mill, Pascall Engineering) for approximately 6 h. The stock solution of dye was made by dissolving $\sim$ 100 mg of the dye (in powder form) into the MY753 resin, using a ultrasonic bath to agitate the solution.

To make a phantom, suitable amounts of the normal resin and hardener were mixed together in the appropriate quantities (3:1) and then calculated amounts of the concentrated stock scattering and absorbing solutions were stirred in. The mixture was degassed using a rotary vacuum pump before being poured into a mould and left to set at room temperature.

4. Measurement of the optical properties of the phantom

The refractive index of the epoxy plastic was measured over the wavelength range 750–850 nm using a picosecond laser and streak camera (Essenpreis *et al* 1993) to time pulses of light travelling through a 280 mm long rod of the clear epoxy. The refractive index, n, is given by

$$n = 1 + c\Delta t/l \tag{1}$$

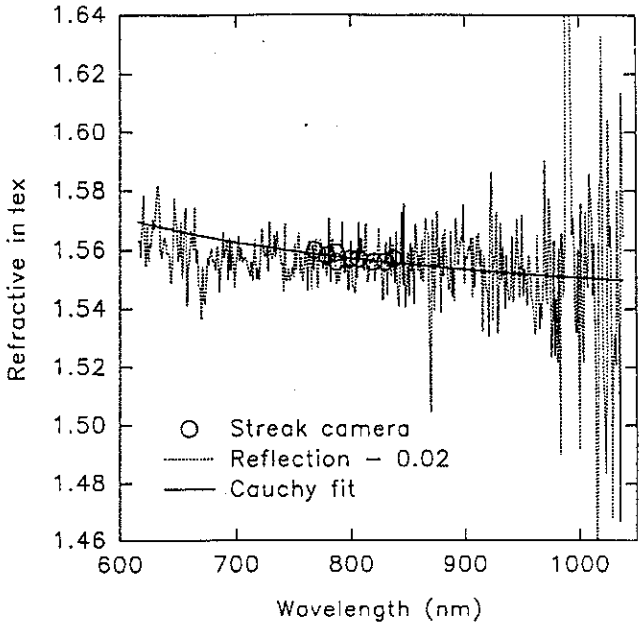

Figure 1. The measured variation of refractive index of the epoxy resin with wavelength.

where l is the length of the rod, c the speed of light *in vacuo*, and Δt the time delay introduced by the rod. The variation of refractive index with wavelength is shown in figure 1.

The variation of refractive index over the wider wavelength range of 650–1000 nm was determined by measuring the transmission, T, through a 3 mm thick, highly polished section of the epoxy. Collimated white light was shone onto the sample, and the transmitted light was collected by a integrating sphere connected via a optical fibre bundle to a spectrographic CCD detector (Cope *et al* 1989). By considering the reflection from both surfaces of the samples, and its absorption coefficient, μ_a (see later), the refractive index can be related to the transmission, thus:

$$n = \left(1 + \sqrt{1 - \sqrt{T e^{\mu_a l}}}\right) \Big/ \left(1 - \sqrt{1 - \sqrt{T e^{\mu_a l}}}\right). \tag{2}$$

This method is very sensitive to the measurement of absolute intensity passing through the sample, and it is very difficult to correct fully for reflection losses at the surface. As a result of this, the absolute value of refractive index measured in this way will often contain a small error, but its wavelength dependence should be correctly determined. The value of the refractive index measured in this fashion is also shown in figure 1. A constant offset of 0.02 has been subtracted from this data, so that it matches the streak camera data, also shown. The Cauchy equation was used to approximate data by

$$n = 1.539 + 11\,605/\lambda^2 \tag{3}$$

where λ is the wavelength in nanometres. This equation was used in the Mie theory calculations.

The refractive index of the silica spheres at 550 nm (1.417) was taken from the manufacturer's data. To extrapolate these data out to NIR wavelengths, the wavelength variation of the refractive index of fused silica was used (Malitson 1972).

The scattering coefficient of the silica spheres suspended in the solid epoxy was measured using an in-line collimated system (Firbank 1994). This consists of an optical bench on which stand a sample holder and two collimators, one of which is connected via an optical fibre to a white light source. The other collimator is a distance of 1 m away, and is connected via another optical fibre to the spectrographic CCD camera. The collimators have an acceptance half angle of 0.15°.

Six samples of epoxy containing different concentrations of scattering particles (from 0.07 to 0.143% by weight) were made. From these, several samples of different lengths were cut (1–5 mm), giving four or five samples for each different concentration. The faces of these samples were roughly polished to a flat surface using 400 grit emery paper.

The samples were held in a 1 cm thick glass cuvette containing ethyl cinnamate ($n_d = 1.55$) in order to reduce surface reflections, and illuminated by collimated white light. The unscattered transmitted light intensity, I, through each sample was measured. The scattering coefficient can be measured from a graph of the log of the intensity against the sample thickness, since

$$\mu_s = -\ln(I/I_0)/l \tag{4}$$

where I_0 is the incident light.

The theoretical scattering coefficient was calculated using Mie theory. A Pascal version of the FORTRAN program given by Bohren and Huffmann (1983) was used to calculate the Mie coefficients, using the measured refractive index of the epoxy, the extrapolated refractive index for the silica spheres, and the size of the particles. Figure 2 shows a comparison between the theoretical and measured scattering coefficients. The scattering coefficients have all been normalized to a 1% concentration (by volume) of the spheres. The scattering coefficient of the samples was measured again after three months, and no significant change was noticed.

The absorption coefficient was measured in a similar fashion although, in this case, an integrating sphere was used to collect the transmitted light. This was used in order to remove any small error that might result from beam deflection due to slight variations in refractive index. Measurements were made on three samples of the pure solid epoxy, and on several solid samples solely containing absorbing dyes. The absorption coefficients are shown in figure 3. The absorption coefficient of the dyes in the solid epoxy was measured again after three months. No change was observable.

To measure the angular distribution of scattered light, two thin samples of low scattering coefficient were made. These samples were held between two glass hemicylinders on a goniometer turntable (Firbank 1994). Collimated white light was used to illuminate the sample, and the scattered light was measured at angles around the sample, using the spectrographic CCD camera. Measurements of the scattered light were made over the first 50°. Beyond this point, measurements could not be made, due to the low intensity of the scattered light levels. These data were extrapolated out from 50° to 180° using Mie theory, and the value of the mean cosine, g, calculated from them using

$$g = \left(\sum f(\theta)\cos\theta\sin\theta\right) \Big/ \sum f(\theta)\sin\theta \tag{5}$$

where $f(\theta)$ is the scattered light intensity as a function of angle and azimuthal symmetry is assumed. Figure 4 shows this, along with the value of g calculated from Mie theory.

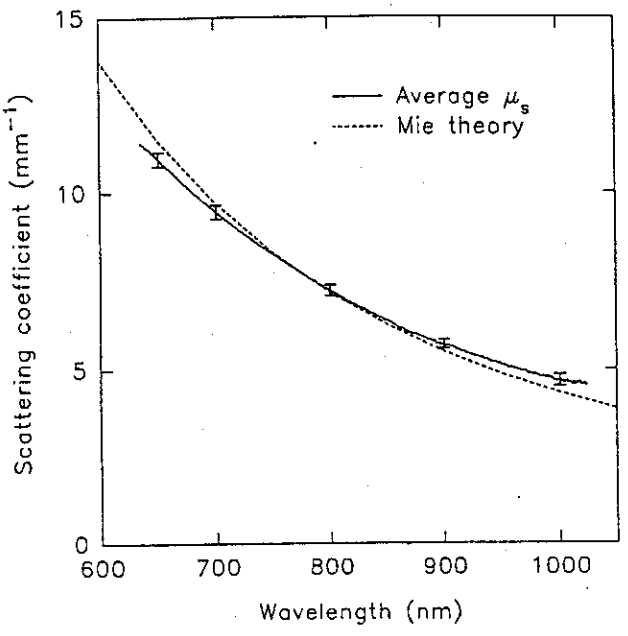

Figure 2. The theoretical and measured variation of scattering coefficient with wavelength. The concentration of spheres in solid epoxy is 1% by volume. Error bars, ±1 SD.

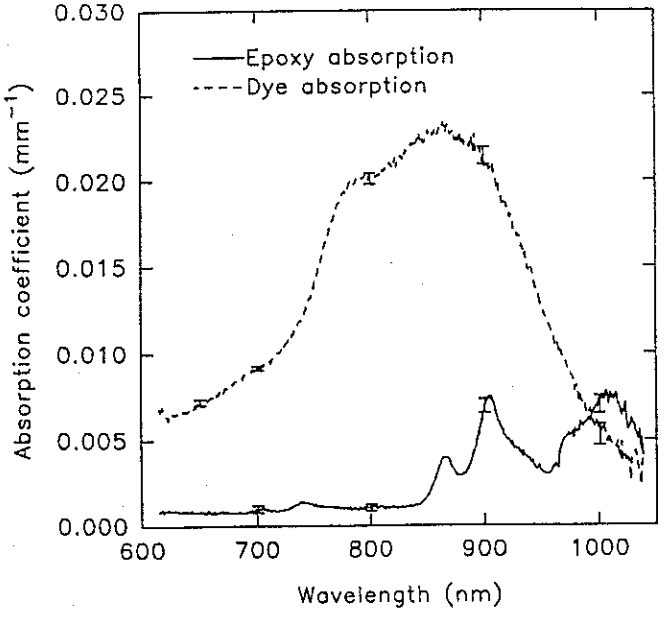

Figure 3. The absorption spectrum of the epoxy resin and of the pure dye in the resin. Error bars, ±1 SD.

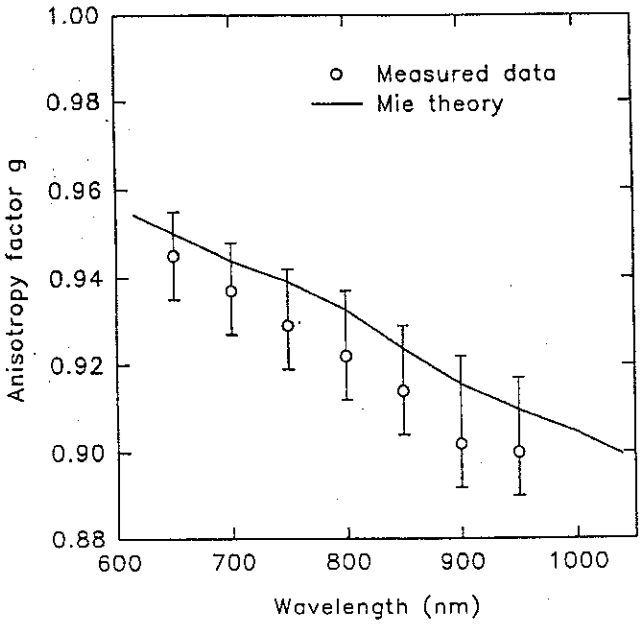

Figure 4. The theoretical and measured variation of g with wavelength. The measured phase function was extrapolated from 50° onwards using Mie theory, and from these data g was calculated. The error bars show the uncertainty in the extrapolation.

5. Discussion and conclusions

We have described an improved phantom for use in NIR spectroscopy and imaging. The phantom was found to be stable in its scattering and absorption properties over a period of three months. The material has the mechanical and chemical stability common to epoxy systems (see Ciba–Geigy data sheets). The scattering properties of the phantom have been shown to agree with predictions from Mie theory. The scattering coefficient of a suspension of 1.82 g of spheres in 100 g of epoxy (1% by volume) is summarized in table 1 for eight wavelengths.

Table 1.

Wavelength (nm)	Measured μ_s (mm^{-1}) (±2%)	g (from Mie theory)	$(1-g)\mu_s$ (mm^{-1}) (±2%)
650	10.9	0.950	0.55
700	9.4	0.944	0.53
750	8.2	0.939	0.50
800	7.2	0.932	0.49
850	6.4	0.924	0.49
900	5.7	0.916	0.48
950	5.1	0.910	0.46
1000	4.7	0.905	0.45

The absorption coefficient for the dye used was approximately 0.01 mm^{-1} at 800 nm for a solution of 1.8 μg of dye in 1 g of resin. It is recommended that persons making their

own phantoms prepare a stock solution of the dye, and measure its absorption coefficient with a standard spectrophotometer, and then use this to determine the quantity of stock solution required for addition to the resin in order to give the desired absorption coefficient.

The optical properties of the phantom are reproducible provided that the component materials are accurately measured and the scattering and absorbing substances are thoroughly dispersed in the resin.

The refractive index of the material is somewhat high in comparison with that of tissue ($n_d \simeq 1.4$), but the effects of this, which are principally the increased surface reflection and longer flight times for photons, can be calculated and allowed for in experimental design.

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