

**NPL REPORT TQE 9**

**FORMULATION AND PROPERTIES OF LIQUID PHANTOMS, 1 MHz  
TO 10 GHz**

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## Formulation and properties of Liquid Phantoms, 1 MHz to 10 GHz

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### ABSTRACT

Measurements of the Specific Absorption Rate (SAR) of energy at radio and microwave frequencies are performed in homogeneous liquid phantoms, which have similar electrical properties to the human tissues of interest. This report reviews the target properties for these phantoms given in existing standards, describes methods for measuring the permittivity and conductivity of phantoms, and presents recipes for making liquids having these properties for the frequency range 1 MHz to 10 GHz. For frequencies between 6 GHz and 10 GHz existing standards do not specify target properties, so these were obtained from human tissue properties, and verified by computer simulations of the human head. Methods for measurement at frequencies below 30 MHz are presented, although simple liquid phantoms cannot provide an accurate match at these frequencies as the required real permittivity exceeds that of de-ionised water. The RF permittivity and conductivity of three liquid phantoms is measured at MHz frequencies by using a 44-mm coaxial sensor and a discontinuous-inner-conductor coaxial cell. Electrode polarisation is observed to be a cause of measurement error at frequencies up to 50 MHz. For two of the phantoms it is found that the conductivity at 64 MHz and 128 MHz, corresponding to the RF frequency for 1.5 Tesla and 3 Tesla Magnetic Resonance Imaging (MRI) respectively, does not differ significantly from the static value, so an inductive conductivity sensor that operates at 5 kHz can be used for measurement.

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## 1 INTRODUCTION

The International Commission on Non-Ionising Radiation Protection (ICNIRP) publishes recommended exposure limits for human exposure to electromagnetic fields [1]. The basic restrictions specified by this standard are based on established adverse health effects. In the frequency range 10 MHz to 10 GHz, the established health effects are due to heating of the tissues in the body by the absorbed electromagnetic energy. Physiological effects are observed if the core body temperature is raised by 1 °C, which corresponds to a whole body Specific Absorption Rate (SAR) of more than 4 W/Kg. For people who are exposed to electromagnetic radiation as a result of their work (occupational exposure) a safety factor of 10 is applied, so that the whole body SAR is restricted to 0.4 W/Kg. For the general public, a safety factor of 50 is applied, so that the whole body SAR is restricted to 0.08 W/Kg. These values are for the average absorption of energy over a six minute period, since this determines how much heating of tissues will occur. The safety factors are to allow for differences in the absorption of energy due to the person's size and orientation relative to the fields, and also reflection, focusing and scattering of the fields. The safety factor for the general public is larger to include groups thought to be at higher risk i.e. babies, children, the old, pregnant women, and people who are particularly susceptible to heating effects as a result of medical conditions or illness. The effect of medical implants is not directly considered by the ICNIRP limits.

Where the body is not uniformly exposed, the basic restrictions also limit exposures to the head, trunk or limbs. Non-uniform exposures occur when the transmitter is placed very close to the person, which is the case for mobile phones. The restrictions for localised exposure are higher than the restrictions for whole body exposure. This is because heating one part of the body has less effect than heating the entire body due to the body's thermoregulatory processes. The basic restrictions are given in Table 1.

**Table 1:** Basic restrictions for exposure to non-ionising radiation in the frequency range 100 kHz to 10 GHz.

|                                    | <b>Whole-body<br/>average SAR<br/>(W/Kg)</b> | <b>Localized SAR<br/>in the head and<br/>trunk<br/>(10 g average)<br/>(W/Kg)</b> | <b>Localised SAR<br/>in the limbs<br/>(10g average)<br/>(W/Kg)</b> |
|------------------------------------|----------------------------------------------|----------------------------------------------------------------------------------|--------------------------------------------------------------------|
| <b>Occupational<br/>exposure</b>   | 0.4                                          | 10                                                                               | 20                                                                 |
| <b>General public<br/>exposure</b> | 0.08                                         | 2                                                                                | 4                                                                  |

For a dielectric material, SAR is related to the electric field in the material and to the rate of temperature increase by

$$SAR = \frac{E^2 \sigma}{\rho} = c \frac{\delta T}{\delta t} \quad (1)$$

where  $\sigma$  is the conductivity of the material (in  $\text{Sm}^{-1}$ ) and  $\rho$  is the density, and  $c$  is the specific heat capacity of the material. Measuring the electric field yields higher sensitivity than measuring the rate of temperature rise.

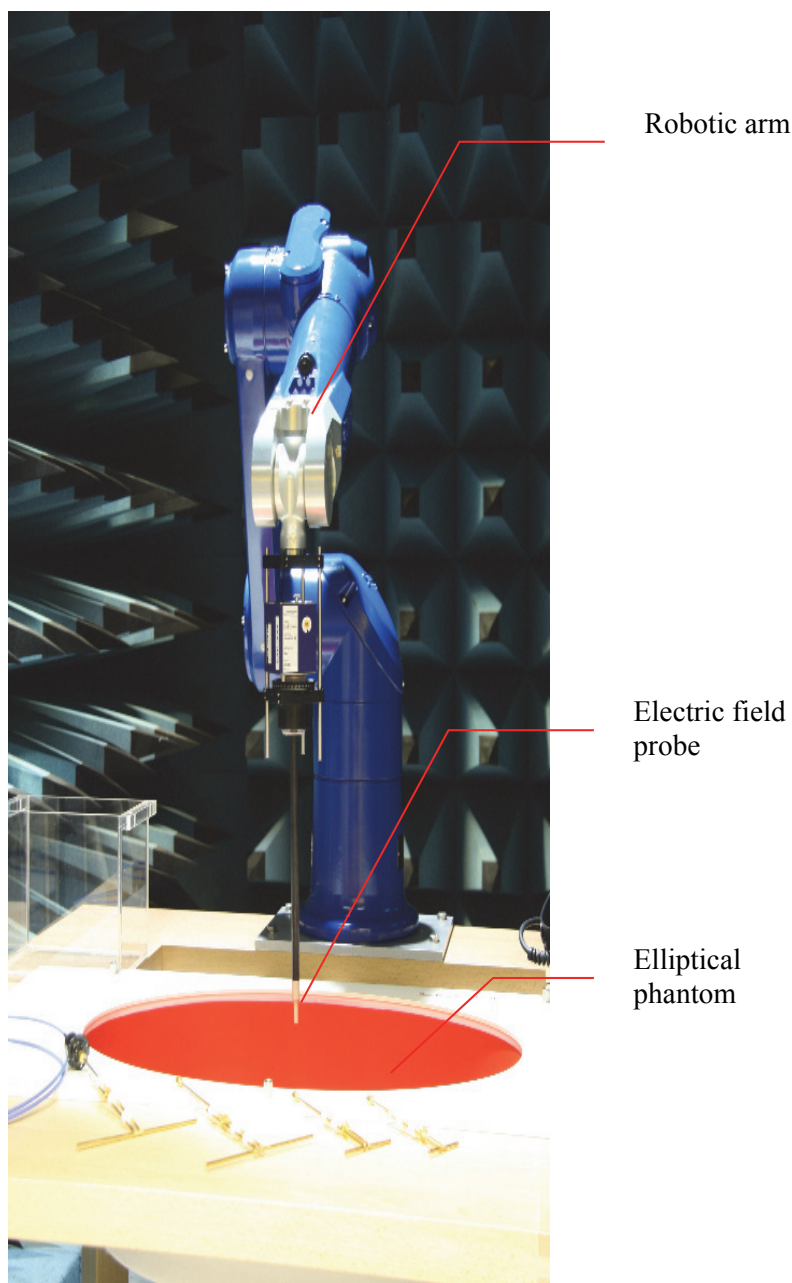


**Figure 1:** SAR measurement system showing an electric field probe mounted on a robot arm above an elliptical phantom. The radiating device under test is located beneath the tank.

Figure 1 shows a typical SAR measurement system with robotic positioning system, electric field probe and an elliptical-shaped vessel containing a liquid ‘phantom’ (also referred to as a ‘tissue equivalent material’). The radiating device under test is located beneath the tank. Scanning the probe through the liquid volume allows the position of maximum SAR from the transmitter to be established and mass (or volume) averaged SAR values to be determined. The permittivity of the phantom modifies the E-field, and hence upon the measured SAR. Therefore, measurements of SAR must be made in a phantom having similar electrical properties to human tissues at the measurement frequency. Solid, liquid and gel phantom materials have been developed for assessing the SAR associated with radiating devices, studying the performance of body-worn antennas and hand-held devices such as mobile phones, and also for a range of applications in medicine (e.g. for evaluating the performance of hyperthermia apparatus). Phantom materials have recently been reviewed [2].

SAR is usually determined using an electric field probe (rather than a thermal probe), in which case a further issue arises: the E-field readings are affected by the permittivity of the phantom, so electric field probes must have been calibrated in a phantom having the correct permittivity. Therefore, traceable and accurate determination of SAR requires that the complex permittivity of phantom liquids is itself determined in a way that can be demonstrated to be traceable and accurate. Furthermore, recipes for phantom liquids that have similar properties to actual human tissues must be developed. For SAR measurements for health and safety testing of appliances such as mobile phones ‘generalised’ target values for body and head tissue have been published in international standards, although in some instances phantoms for specific types of tissue (grey matter, etc.) may be needed. The complex permittivity of tissues is frequency dependent, so a range of recipes for phantoms are needed. Where possible, broadband recipes [3] that are within specification for an extended range of frequencies are preferred, as fewer types of phantom are then needed. The specifications for phantoms, and the methods for traceable measurements of their complex permittivity, provide the rationale for the work described in this report. The permittivity and conductivity of phantom materials may show significant dependence (up to 5% per °C) so the temperature must be controlled to ensure that phantoms are within specification. Laboratories typically operate at a room temperature in the range 21 °C to 22 °C to provide a comfortable working environment. The measurements presented in this report were made at 22 °C.

Target values for the dielectric properties of phantoms from IEC 62209 [4-5] and FCC standards [6] are reproduced in Tables 2 and 3. These have been derived from a compilation of dielectric data for the human tissues (bone, muscle etc.) published by Gabriel [7]. The target values do not reproduce tissue properties precisely, but have been chosen to be conservative so that SAR values measured in phantoms exceed those that occur in an exposed human. They are also chosen to be realisable with easily available materials. Some compromises are therefore needed, for example, at the lowest frequencies permittivity target values  $\leq 80$  are adopted to be compatible with aqueous phantoms, even though the permittivity of tissues is considerably greater. The IEC standard specifies the same target permittivity and conductivity for head and body. Some of the IEC target data is reproduced in Table 2. The FCC standard specifies the same values for head phantoms as the IEC head/body phantom, but alternative values are given for the body phantom (Table 3).

For head phantoms, target conductivity data is based on that of grey and white matter only, and a true anatomical model that incorporates the cranial bones is not applied. Simulations [8] using a multi-layer model that incorporates bone and skin show that a conservative assessment of SAR is obtained. The conductivity of body tissue is based on muscle alone (as this has a higher conductivity than most other types of tissue). On account of the conservative approach the target values adopted are 20% greater than the conductivity of muscle.

**Table 2:** Example generalised target values published in IEC standard 62290 [4-5] which, currently, specifies target values for the range 30 MHz to 6 GHz. The same target values for the head and body are specified by this standard.

| Frequency<br>(GHz) | Head and body phantom |                 |
|--------------------|-----------------------|-----------------|
|                    | $\epsilon'$           | $\sigma$<br>S/m |
| 0.03               | 55.0                  | 0.75            |
| 0.15               | 52.3                  | 0.76            |
| 0.9                | 41.5                  | 0.97            |
| 2.45               | 39.2                  | 1.80            |
| 5.8                | 35.3                  | 5.27            |

**Table 3:** Example generalised target body values published in FCC standard [6] for the frequency range 150 MHz to 5.8 GHz. This standard specifies different target values for the head and body. Head values are as given in Table 2.

| Frequency<br>(GHz) | Body phantom |                 |
|--------------------|--------------|-----------------|
|                    | $\epsilon'$  | $\sigma$<br>S/m |
| 0.15               | 61.9         | 0.80            |
| 0.9                | 55.0         | 1.05            |
| 2.45               | 52.7         | 1.95            |
| 5.8                | 48.2         | 6.00            |

## 2 DIELECTRIC MEASUREMENTS ON PHANTOMS

Laboratories involved in the measurement of SAR are accustomed to expressing dielectric properties [9, 15] of phantoms and tissues in terms of the *real part of the relative permittivity*  $\epsilon'$  (often referred to as ‘the permittivity’) and the *total conductivity*  $\sigma = \sigma_i + \sigma_d$  where  $\sigma_i$  represents the ionic contribution and  $\sigma_d$  is the dielectric contribution. For materials with polar molecules,  $\sigma_d$  represents loss caused by *dipolar relaxation*. In some other texts  $\sigma$  is used to represent ionic conductivity only (see reference [9] page 19 for more discussion). Conductivity is usually presented in units of S/m. Instruments for determination of dielectric properties actually measure the *complex permittivity* ( $\epsilon^* = \epsilon' - j\epsilon''$ ). The total conductivity is calculated from a simple formula,  $\sigma = \omega\epsilon_0\epsilon''$ , which is a convenient way to represent losses, as  $\sigma$  has minimal frequency independence (see Figure 2). Complex permittivity is normally determined from measurements of the complex S-parameters of a coaxial sensor, or a transmission or reflection cell [10-11], that is in contact with or filled by a sample of the material to be measured. The most suitable technique is often determined by the required frequency range. Some methods are only suitable for liquids, in which case the sample viscosity can also be a consideration. Vector Network Analysers make such measurements very convenient. In this section, the procedures used for different types of sensor and cells for measurements on phantoms are discussed.

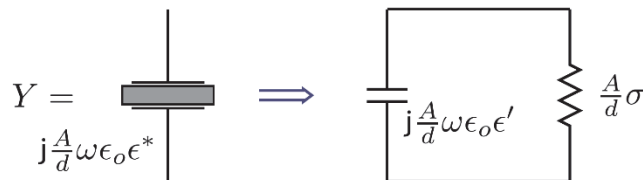


**Figure 2:** Capacitor/resistor admittance (Y) model of a lossy dielectric (A is plate area, d is plate separation).

Dielectric *reference liquids* [12] with high chemical purity for which dielectric data is available are used for calibration and for checking of measurements. In most cases polar [10] liquids are used as these have high permittivity (comparable to that of phantoms) at RF and low microwave frequencies. High purity samples must be used (these are available from chemical suppliers). The best characterised liquid is water, for which data is available from several sources [13]. A single-Debye relaxation model for water is accurate up to at least 30 GHz [10]. For methanol, ethanol, ethanediol and dimethyl sulphoxide (DMSO) traceable reference data has been published in NPL Report MAT 23 [14]. This data, however, extends only to 5 GHz. At this time, extrapolation of data in reference [14] may be best way of obtaining accurate reference data for certain liquids in the 5 GHz to 10 GHz range. To make the calculation of complex permittivity and the associated uncertainty easier, a computer program (*Qmat23*) has been written<sup>1</sup>. This contains look-up tables of uncertainty, which have been extended to 10 GHz for methanol, ethanediol and DMSO on the assumption that the single-relaxation models used remain accurate (see Section 2.5). The Debye- $\Gamma$  relaxation model used for ethanol becomes inaccurate above 4.5 GHz at room temperature.

It is important to note that liquid phantoms contain dissolved salts, which result in much increased *Electrode Polarisation* (EP) effects in measurements in electroded systems. These cause error in the measured permittivity and conductivity in the lower part of the spectrum. There is an extensive literature on EP; however reference [15] is especially recommended. EP occurs because electrons are able to pass from electrolyte to electrode, whereas ions cannot. Double layers (surface charges + adsorbed ions) therefore build up at the electrodes [16]. At the lowest frequencies apparently ‘giant’ values of permittivity (e.g.  $10^7$  at 100 Hz) for ionised liquids can be measured as a result of frequency-dependent capacitance associated with the double layers. These artefacts of EP are erroneously reported as valid measurements in some papers. The effect of EP is very variable as it depends on the surface chemistry and topography of the electrode surfaces. EP can be reduced by using electrode materials that have porous or fractal surfaces to give a high effective area [17], such as platinum-black and sandblasted-platinum [15, 18-19]. EP increases rapidly as the frequency is reduced; high effective area electrodes shift the frequency range for which EP is significant downwards. Corrections based on circuit models have also been proposed [18].

In practical measurements on phantom liquids in systems with e.g. gold-flashed brass or stainless steel electrodes, an enormous increase in the measured permittivity and a significant reduction in measured conductivity are observed at frequencies at  $\approx 1$  MHz as a consequence of EP. The effect of EP falls away as the frequency is increased. The maximum frequency at which EP has significant effect depends on ionic concentration. Measurements made using a coaxial reflection cell that are presented in this report would suggest that for typical phantom recipes EP effects are significant up to  $\approx 50$  MHz. It is recommended that ionic liquids are not used for calibration of electroded systems at frequencies  $\approx 100$  MHz, except in the special case of conductivity meters and probes (Section 2.1).

It only takes a very small amount of ionic contamination to substantially increase the effects of EP in samples of polar liquids measured in electroded systems. If measurements at frequencies below 50 MHz are to be made, then prior to measurements thorough rinsing of beakers, the sensor or cell etc. with high-purity water or alcohol is therefore essential. High purity polar liquids generally have low ionic conductivity, but even ultrapure samples of some liquids are slightly conducting as a result of dissociation or dissolved  $\text{CO}_2$ . This applies to alcohols (especially methanol) and water. In measurements made with an admittance cell with gold-flashed brass electrodes it is found that, to avoid significant effects from EP, the frequency must be  $\gtrsim 200$  kHz even for high-purity samples of these liquids [20].

In Sections 2.1 to 2.4 methods for characterising phantoms are described. Figure 3 is a ‘key’ to the techniques that describes the frequency ranges over which they can be applied.

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<sup>1</sup> It is intended that *Qmat23* will be made available via the NPL website at a future date.

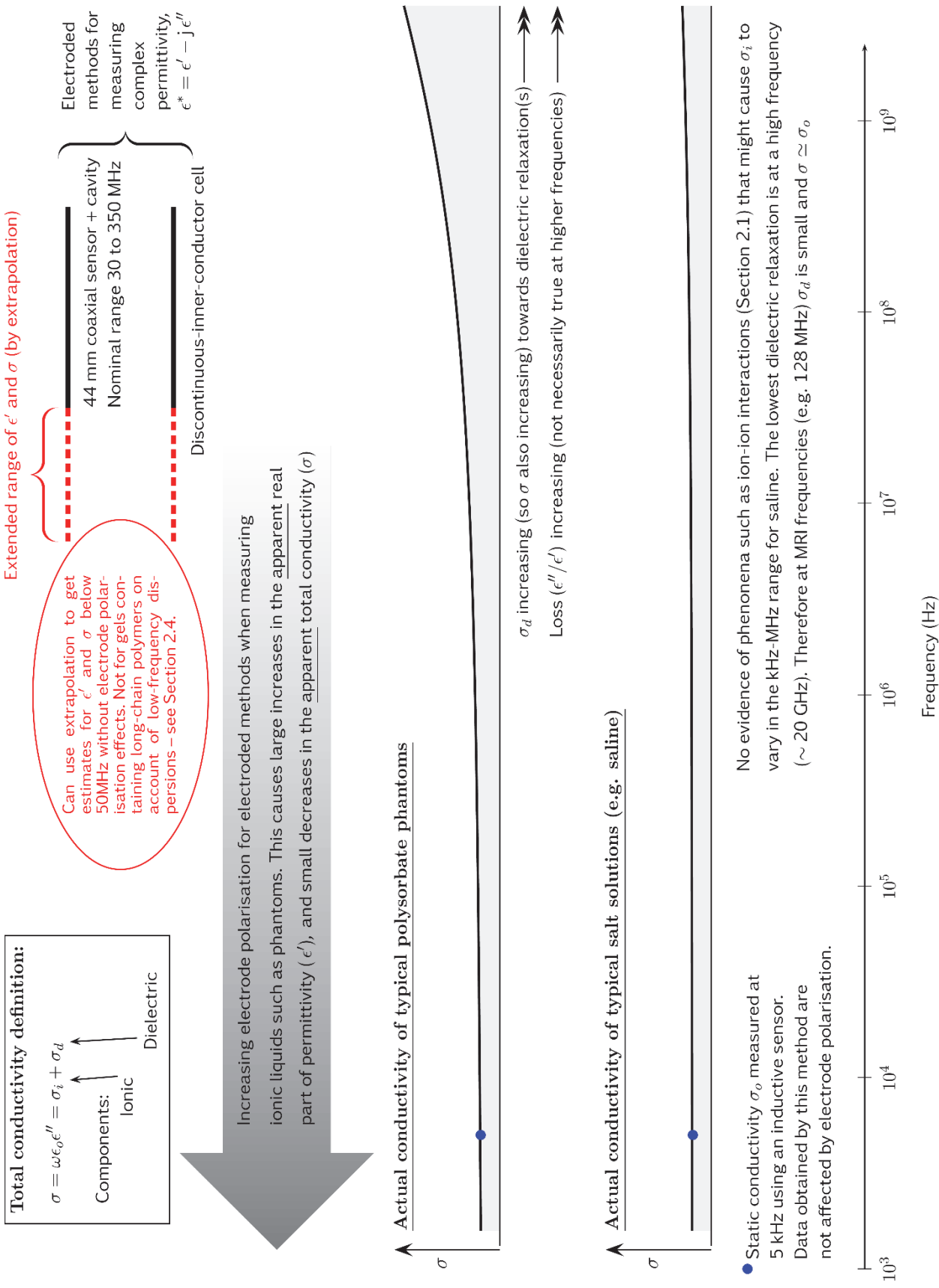


**Figure 3:** A key to the techniques for measuring phantoms described in Sections 2.1 to 2.4

## 2.1 MEASUREMENT WITH CONDUCTIVITY METERS

At kHz frequencies, conductivity can be measured with commercially-available instruments that are typically used for measurements for water treatment, monitoring salinity, in conventional and hydroponic agriculture, and for monitoring bio-reactions. In this report the measured quantity will be referred to as the *static* conductivity, but elsewhere it is often referred to as the *DC* conductivity. Measurements are not made at DC as electrolytic reactions occur at the electrodes. Two main types instrument are available: electroded conductivity cells [15, 21], and electrodeless sensors based on electromagnetic induction [18, 21-23]. Electroded conductivity cells are available in two- and four-electrode versions. The idea of using four-electrodes, as opposed to two, was introduced to reduce the effects of EP (it is, however, reported that measurements of the real part of permittivity by using four-electrode cells are subject to unwanted parasitic effects – see [24] for discussion). Measurements of the conductivity of tissue using a four-electrode conductivity cell are reported in reference [25]. Electrodeless inductive sensors (Section 2.1.2) have the advantage that measurements are unaffected by EP.

Conductivity reference liquids (traceable to e.g. NIST) for calibration of conductivity meters that work in the kHz range are readily available. Above approximately  $\approx 50$  MHz traceable methods (e.g. using coaxial cells – see Section 2.3) allow measurements of the permittivity and conductivity that are not subject to significant error due to EP. This leaves a significant ‘gap’ in the frequency coverage of traceable methods for measuring conductivity, and in the availability of suitable reference liquids. For characterising phantoms at frequencies in the ‘gap’ data extrapolation methods can be applied (Section 2.4) if certain assumptions are made. Inductive methods are of considerable interest as potentially they can work at frequencies in the ‘gap’ and can measure both permittivity and conductivity; however instruments based on induction that work at MHz frequencies are not readily available. Conductivity meters that work in the kHz range are, however, available commercially.

### 2.1.1 Can measurements on liquid phantoms made using kHz conductivity meters be applied at MHz frequencies?

Measurements of the *static* conductivity  $\sigma_o$  made at kHz frequencies (with probes that avoid the effects of EP) can be applied at MHz frequencies if:

- The ionic conductivity  $\sigma_i$  at the frequency of interest can be assumed to differ little from  $\sigma_o$ .
- It can be assumed that  $\sigma_d \ll \sigma_i$  as dielectric loss peaks occur at significantly higher frequencies than the kHz-MHz range.

There are a number of theoretical studies [26-28] of the dynamics of ions in solution, which show that there are loss phenomena that potentially could occur at kHz or MHz frequencies (which would cause  $\sigma_i$  to be frequency dependent). A relaxation phenomenon known as the *Debye-Falkenhagen* effect occurs at low MHz frequencies. This is a small effect that arises as a displaced ion is subject to a restoring force caused by the presence of the ‘atmosphere’ of surrounding ions. The motion of an ion has an associated time constant and therefore lags the applied E-field, which gives rise to a dielectric loss peak. Coulombic interaction may cause the formation of *ion-pairs* that have dipole moments – resulting in a dielectric loss peak. Whether or not such effects are significant for phantoms will depend on the recipe and on the ion concentration. Results presented in reference [19] for saline (up to 0.02 molar) show that conductivity does not change significantly between 100 kHz and 10 MHz, which is in compliance with the first of the two requirements given above.

Dissolved ions generally lower the permittivity and increase the relaxation frequency of an aqueous solvent [29]. Measurements of the static conductivity of salt solutions are compared with RF measurements in this report (Section 2.4.1). They are found to be consistent for (i) a saline phantom used for MRI-implant testing at 64 MHz and 128 MHz and (ii) a conductivity reference liquid obtained from a chemical supplier (an unspecified salt solution) in the frequency range 3 MHz to 350 MHz. It can be concluded that phantoms based on salt solutions for use at MRI frequencies (Section 6) can be characterised with sufficient accuracy using low-frequency conductivity meters, as the conductivity does not change significantly between 5 kHz and 128 MHz. This is consistent with the high relaxation frequency of salt solutions (comparable to that of water, 17 GHz).

For more complex recipes, e.g. those with organic constituents, it is not necessarily the case that the static conductivity can be applied at MRI frequencies with sufficient accuracy as relaxation phenomena occur at lower frequencies. In Section 2.4.2 it is shown that the conductivity of a gel phantom at the 128 MHz MRI frequency is approximately 8% greater than the static conductivity. If the RF conductivity of a phantom is only marginally greater than its static conductivity, then it may be sufficient to use the static conductivity in RF experiments to determine SAR. Exposure to RF in a test facility will then result in larger-than-expected temperature rises so the determination of SAR will be conservative [30].

### 2.1.2 Inductive sensing

Inductive conductivity meters, based on mutual coupling between coils (Figures 4 and 5), are available from several manufacturers. These are a robust alternative to electroded conductivity cells that do not require special cleaning of electrodes. They provide relative measurements of conductivity at kHz frequencies, but can be calibrated by using a conductivity reference liquid purchased from a chemical supplier. Traceability at kHz frequencies can therefore be obtained. Methods of reducing the effects of signal leakage, acoustic coupling, and stray mutual inductance inside the sensor (which are limitations for the technique) are described in a number of patents [31-32]. There are, however, rather few publications in the open literature. To obtain accurate measurements using the sensor shown in Figure 5, samples should be contained in a beaker at least 90 mm in diameter (with the sensor positioned at the centre).

Reference [33] describes the Hewlett-Packard E5050A colloid probe; an inductive sensor that can be used in conjunction with an LCR meter at RF frequencies in the range 75 kHz to 30 MHz. Unfortunately this device is no longer manufactured. As vector measurements are made, it is possible to measure the complex permittivity. Recent work [23] examines theoretical assumptions made in reference [33] and, for an inductive sensor based on two concentric toroidal cores, presents a more rigorous analysis. A calibration scheme requiring measurements on air and two reference liquids is presented.

### 2.1.3 Triangle-wave voltage technique

In this method a low-frequency (up to ~100 kHz) triangular-shaped waveform is applied to a sample between parallel plate electrodes [34]. Measurements of voltage and current as a function of time are made using a digital oscilloscope, from which the cell resistance and capacitance are obtained. Therefore conductivity and permittivity can be obtained. In reference [34], the effect of EP on measurements of the conductivity of salt solutions in a cell with fixed electrode separation is studied. A technique for reducing the effects of EP by using a variable electrode-gap cell is developed.

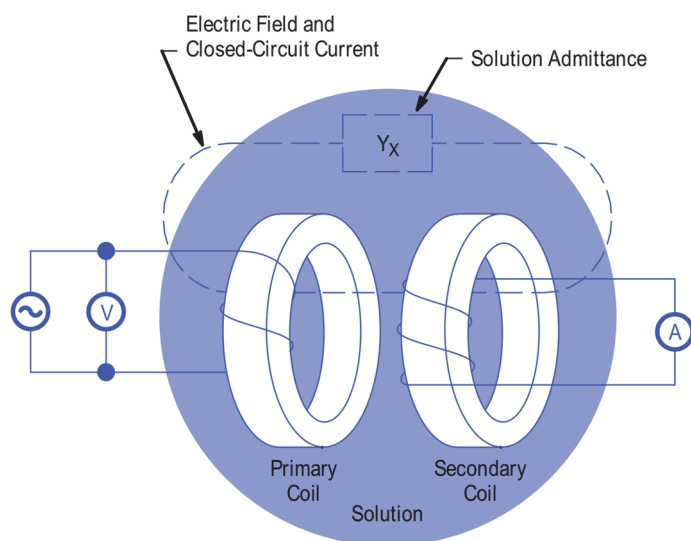


**Figure 4:** Electromagnetic induction method (copyright Hewlett-Packard Company, reproduced from reference [33] with permission). Measurement of complex admittance enables both permittivity and conductivity to be obtained at RF frequencies.



**Figure 5:** A commercial inductive probe (Mettler Toledo model *InPro 7250 ST*) for measurement of static conductivity. All of the measurements of static conductivity presented in this report were made with this probe in conjunction with conductivity-meter model *M400 Type 1 Cond. Ind.* This system does not allow permittivity to be measured.

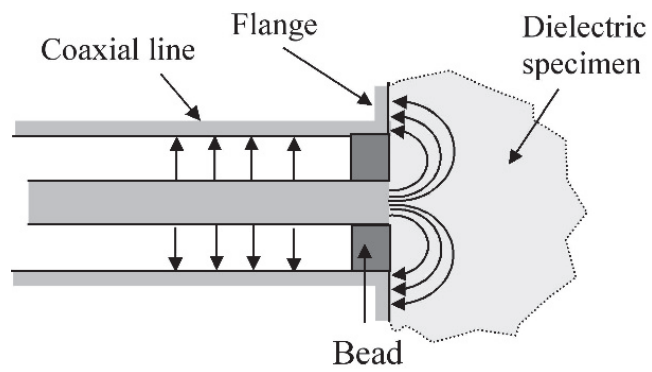


**Figure 6:** Schematic of an open-ended coaxial sensor



**Figure 7:** NPL Ø 7-mm coaxial sensor (frequency range 100 MHz to 10 GHz). The bore diameter is 7 mm and the flange diameter is 25 mm.

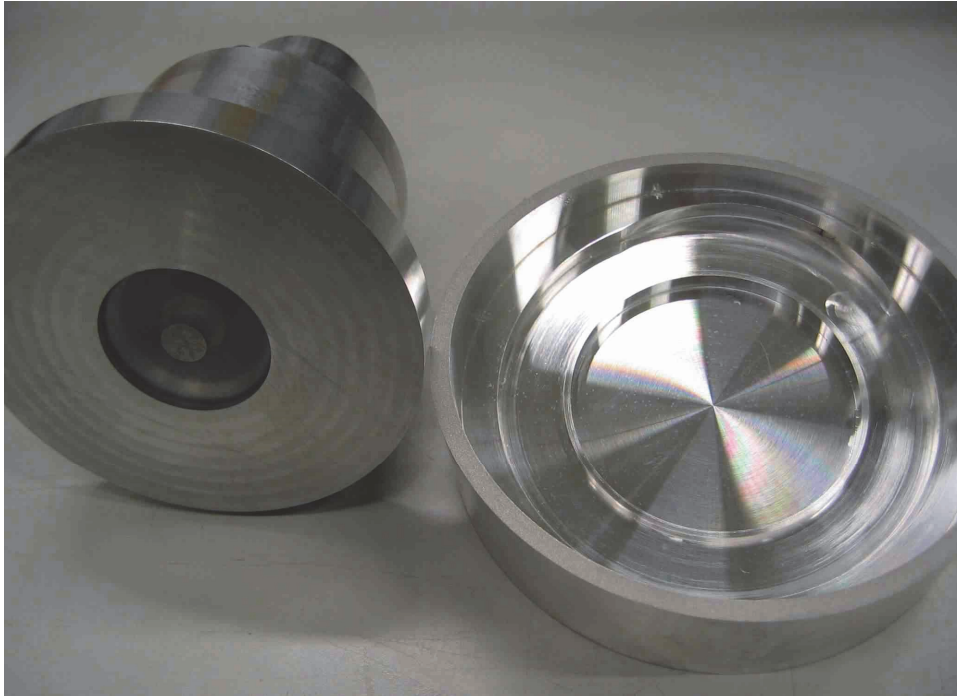


**Figure 8:** NPL Ø 44-mm coaxial sensor (left) for the frequency range 30 MHz to 400 MHz. The sensor can be used open-ended if samples are available in sufficient volume. Alternatively, it can be used in combination with a cylindrical cavity. The cavity shown on the right is a recess ( $\text{Ø } 80 \times 6 \text{ mm}$  depth) cut into an aluminium block that also provides a reservoir for samples. The base is sloped to allow air bubbles to escape.

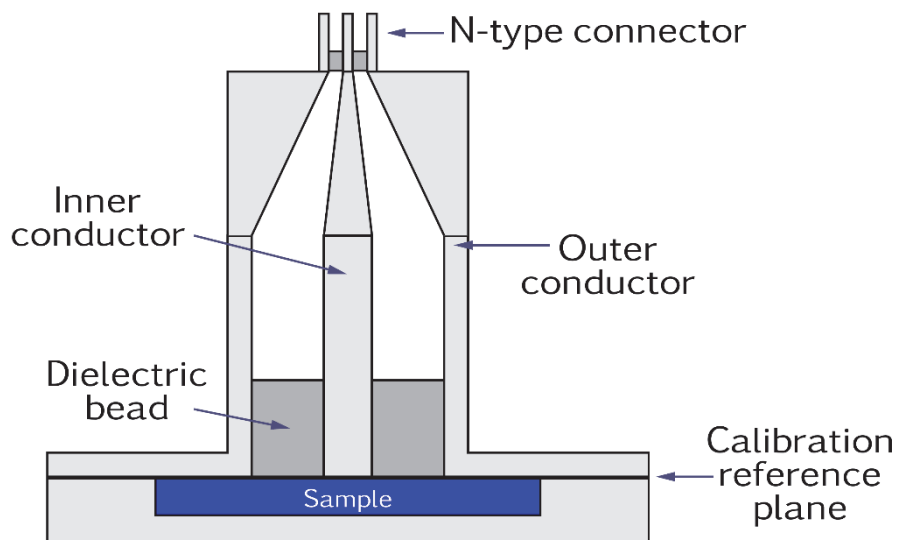


**Figure 9:** Coaxial sensor combined with a cylindrical cavity.

## 2.2 COAXIAL SENSOR METHODS FOR 30 MHz TO 10 GHz

Coaxial sensors [10, 35-36] are widely used for measuring the complex permittivity of liquids, gels, and malleable solid materials. Complex permittivity is calculated from the measured reflection coefficients at each frequency. An open-ended geometry (Figure 6) is most commonly used (often referred to as an ‘open-ended coaxial probe’). If the flange is sufficiently large this approximates to a *calculable geometry*, so traceable measurements can be obtained using tested modal analysis software. Prior to use the system (VNA + coaxial sensor) must be calibrated to define a reference plane at the face of the sensor and correct for the effects of mismatches. The method of calibration that is used most often requires measurements on a reference liquid, air, and a short-circuit (e.g. copper foil). In order to get reliable measurements, careful consideration of the measurement and calibration procedure is necessary as there are a number of potential pitfalls – for example flange and volumetric resonances [36] may occur for large sensors (bore diameter  $\lesssim 7$  mm). To avoid such resonances during calibration, it is necessary to select a calibration reference liquid that is appropriate for the size of sensor and the frequency range. Reference [35] describes calibration procedures for coaxial sensors in detail.

It is recommended that calibrations are tested with a ‘check’ measurement on a reference liquid which is different from the calibration reference liquid. The reference liquid can be used as an aid to the estimation of uncertainties of measurements on phantoms. However, this method of assessing uncertainty is satisfactory only if the reference liquid and the phantom being measured have similar properties. A reference liquid that matches the properties of tissue reasonably well at the required frequency may not be available (especially at frequencies below  $\approx 100$  MHz). *Monte-Carlo Modelling* [35] enables evaluation of uncertainty throughout the frequency range using a comprehensive model that includes both calibration and measurement processes. The authors’ software also applies a small minimum uncertainty (e.g. 1% at  $k=2$ ) which is added in quadrature to account for geometrical imperfections which the numerical model is not able to account for. From such simulations two useful observations can be made: (i) uncertainty is in many cases fairly independent of the actual value of the permittivity at a given frequency, and (ii) the uncertainty associated with real and imaginary parts is in most cases almost equal. For these reasons, it is preferable to describe the accuracy of coaxial sensors by the actual numerical uncertainty rather than the percentage. For example, the uncertainty of measurements on samples with permittivity  $\epsilon' = 80$  and  $\epsilon' = 20$  might be 1.2% and 5% respectively, but it provides more insight if the measurement uncertainty is claimed to be  $\pm 1$  for samples with permittivity in the range 20 to 80.

Figure 7 shows a  $\varnothing 7$ -mm coaxial sensor with  $\varnothing 25$ -mm flange. Its nominal frequency range is 100 MHz to 10 GHz. Below this range uncertainties of measurements on phantoms become too large. Above this range, calibrations are not reliable for the open-ended geometry as there are frequencies at which the flange resonates during the ‘air’ (open) measurement.

Some general guidelines for the choice of reference liquids for calibrating the 7 mm open-ended coaxial sensor can be given (these apply also to larger sensors although the specified frequency ranges are reduced): At frequencies  $\lesssim 1$  GHz, high permittivity liquids with loss tangent  $\gtrsim 0.3$  are not measurable with large coaxial sensors as flange and volumetric resonances occur. Water is unsuitable as a calibration reference liquid and aqueous solutions are not generally measurable. Methanol can be used for calibration (where it is possible to use this toxic liquid) but only in the range  $\approx 2.5$  GHz to 10 GHz and below<sup>2</sup>  $\approx 0.7$  GHz. Ethanol is suitable for calibration at frequencies up to  $\approx 2.5$  GHz as its high loss ensures that flange and volumetric resonance effects are negligible. At frequencies above 2.5 GHz, however, it is not a good choice as its permittivity is too low. Further information on the choice of liquids is given in

<sup>2</sup> To measure methanol at  $\gtrsim 10$  MHz requires very clean equipment as the slightest ionic contamination can cause significant error on account of electrode polarisation effects. The minimum frequency for measurement by using a 7-mm sensor is approximately 100 MHz.

reference [35]. Section 2.5 discusses the availability of reference data for the 5 GHz to 10 GHz range.

Ø 3.5 mm (and smaller) flanged coaxial sensors have the advantage that aqueous liquids are measurable without significant flange or volumetric resonances. Pure (or deionised) water is suitable for calibration over the entire band (200 MHz to 20 GHz for a Ø 3.5 mm sensor). For small sensors it is more difficult to obtain a reliable short-circuit measurement during calibration as the contact area is smaller.

For measurements below 100 MHz larger sensors are needed to give acceptable uncertainty. Figure 8 shows a Ø 44 mm sensor that has a working frequency range of approximately 30 MHz to 350 MHz. The sensor can be used open-ended; but the required volume of sample can be greatly reduced if an alternative calculable geometry that uses an attached cylindrical cavity [10, 37] is used (Figure 9). Monte Carlo Modelling software for evaluating uncertainty has been extended to allow it to be applied to sensors with an attached cylindrical cavity. Some example measurements and evaluated uncertainties are shown in Table 4. The disadvantage of using a closed-end cavity is that air bubbles in liquid samples are concealed.

### 2.2.1 The effects of bubbles and microbubbles

Measured values of permittivity and conductivity made using a coaxial sensor can be reduced significantly (perhaps by a few percent) if there are bubbles in close proximity to the sensor, especially near the inner conductor. This is a particular problem for polysorbate-based phantoms as bubbles are not easily removed. When measuring high-permittivity liquids that also have high-surface tension, such as water, wiping the wetted face of the sensor with a gloved finger (e.g. with a nitrile glove) is observed to increase subsequent readings of the permittivity by typically 0.5%. This is attributed to microbubbles that cannot be seen by the unaided eye. The wiping procedure is recommended when measuring aqueous and viscous samples (especially if used for calibration) to enable the highest measurement precision to be obtained.

### 2.2.2 The penetration depth for open-ended coaxial sensors

Fringing electric fields between outer and inner conductors penetrate samples are typically evanescent and short-range. They can be compared to fringing fields around the edges of the electrodes of a capacitor. For large sensors ( $\approx 7$ mm), however, the wavelength may become comparable to its dimensions in the presence of typical high-permittivity specimens, in which penetration depth increases as the sensor starts to behave like an antenna and radiate [36]. Flange and volumetric resonances referred to above occur when  $\tan\delta \gtrsim 0.3$ . This regime is normally avoided as these cause significant measurement errors.

Penetration depth is studied in the literature [38-39] in the context of biomedical measurements; interpretation of measurements on a layered material such as skin requires it be known if the 'perceived' permittivity is largely determined by the material closest to the probe, or if underlying layers also have significant effect. For a bi-layer model (Figure 10) comprising of a polymer cylinder immersed in a tank of water or saline, it is found that there is a region in which the perceived permittivity has an almost linear dependence on the thickness of the layer closest to the sensor (i.e. the liquid) [38-39] – see Figure 11. The Histological Sensing Depth (HSD) can be defined as the separation between the sample, and an extrapolated point at which the linear fit diverges from the actual measured behaviour by 20% of permittivity. As a convenient generalisation, for samples of typical tissue-equivalent materials or biological tissues, the HSD is approximately 1/6th of the bore diameter of the sensor, and does not vary greatly with frequency or the sample permittivity. Reference [39] provides a more detailed discussion of the HSD for sensors of a range of sizes.

It is important to understand that the HSD is defined in terms of the ‘perceived’ permittivity of a bi-layer or inhomogeneous sample. The sample depth that is required to obtain precise measurement of homogeneous materials such as liquid phantoms is considerably greater. Samples of reference liquids and tissue-equivalent materials are normally available in plentiful amounts, so to ensure that the precision of measurements is not limited by the effect of boundaries, it is recommended that the depth of samples should be a few times the diameter of the bore of the sensor or greater.

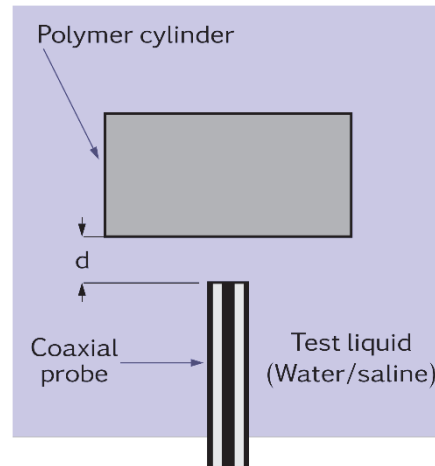


**Figure 10:** Bi-layer model for evaluation of sensing depth.

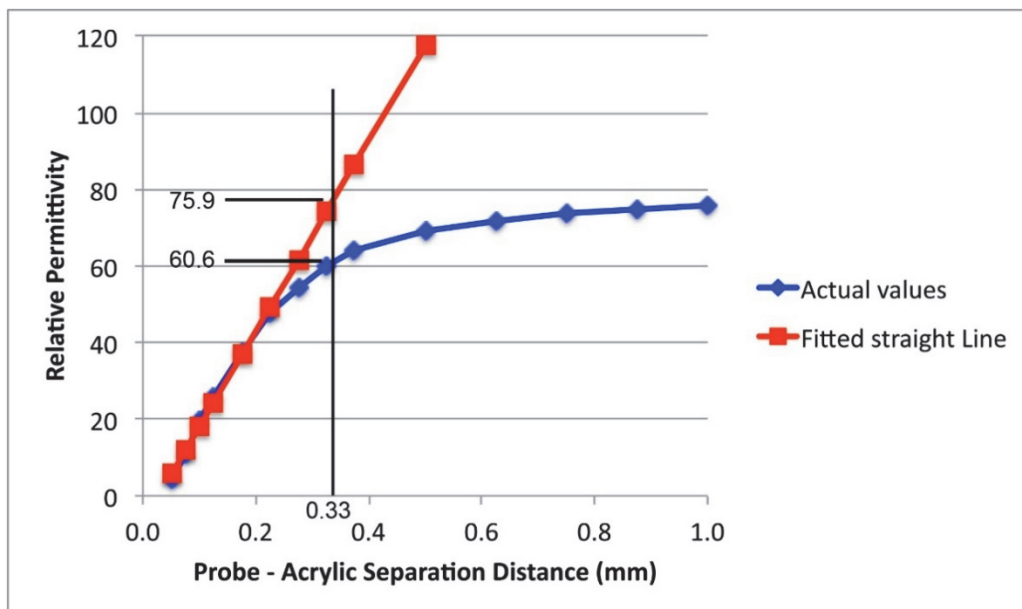


**Figure 11:** Perceived permittivity for the system shown in Figure 10 for water and acrylic cylinder layers. A Keysight slim-form probe (2.2 mm external diameter) was used.

Acknowledgement: This figure was produced by P M Meaney and is reproduced with his permission.

### 2.3 MEASUREMENT IN THE 10 MHz TO 350 MHz RANGE USING A DISCONTINUOUS-INNER-CONDUCTOR REFLECTION CELL

A discontinuous-inner-conductor cell [40] (Figures 12 and 13) is well-suited to obtaining measurements at frequencies below a few hundred MHz because it has high sample capacitance and only requires a small volume of samples. It gives direct traceability to impedance standards without the use of calibration reference liquids (although they could be used if desired). The cell used at NPL is based on 14-mm coaxial line and has inner conductors (Figure 14) of several lengths as open-circuit calibration standards. The reflection coefficient of the open-circuit standards is traceable to dimensional measurements [40]. Short-circuit and load terminations can also be used for calibration. The bead is ‘removed’ by the calibration procedure. Data presented in reference [14] at frequencies in the range 100 MHz to 1 GHz was obtained using this cell with a truncated inner conductor 5-mm in length. A longer truncated inner conductor (e.g. 18-mm) can be used to obtain smaller measurement uncertainties at frequencies below 100 MHz (Table 4 shows some example measurements). To obtain the best accuracy high machining tolerances are needed. An alternative design of cell is described in reference [41].

The uncertainty of measurements made with the discontinuous-inner-conductor cell can be evaluated from calculated sensitivity coefficients and estimates of the uncertainty associated with the measured reflection coefficients and dimensions [40]. In a number of experiments it has been found that measurements of  $\epsilon'$  for non-aqueous polar reference liquids such as methanol are very consistent with reference data [14]. The measurement variability for pure water samples, however, is observed to be slightly greater than that expected (although there seems to be no evidence of a systematic error). In other words, Type A uncertainties for aqueous samples ( $\epsilon' \approx 80$ ) are slightly under-estimated, while for e.g. methanol ( $\epsilon' \approx 33$ ) they appear to be realistic. The reason for this is unknown, although microbubbles could be a factor. In this report, uncertainty evaluations for measurements of the permittivity and conductivity of aqueous samples by this method are subject to additional 1% ( $k=2$ ) contributions to account for this variability.

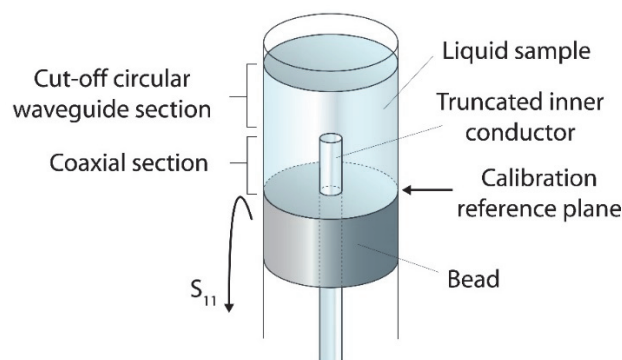


**Figure 12:** Schematic of the discontinuous-inner-conductor cell. For the results presented in the report, a cell internal diameter 14.288 mm was used. The truncated inner conductor was 6.204 mm diameter  $\times$  18 mm. The conductor diameters are compatible with MPC14/ GR900 connectors.

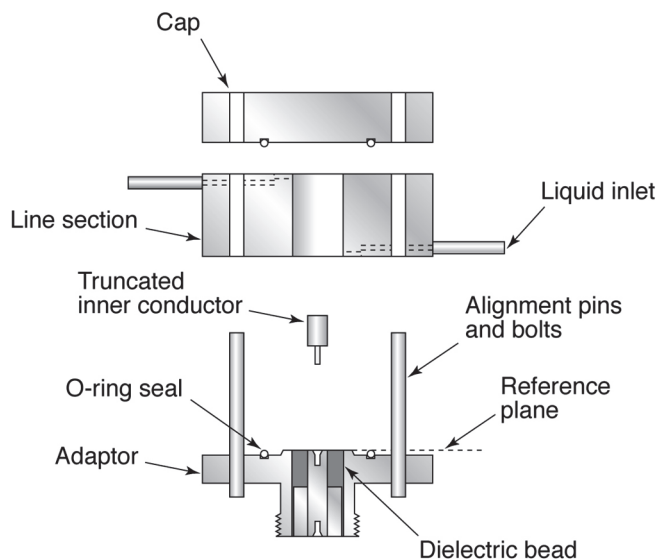


**Figure 13:** Mechanical design of the discontinuous-inner-conductor cell



**Figure 14:** Truncated inner conductors (lengths 7, 12, 18 and 25 mm) that can screw in place of the spring-finger collet (shown right) of an MPC14/ GR900 coaxial-line connector. These are used for measurement on liquids and also as offset open-circuit standards for calibration.

**Table 4:** Measurements on a 0.15 GHz head phantom liquid based on polysorbate 20 (see Table 9) at 22 °C made using a 44-mm coaxial sensor with cavity, and a discontinuous-inner-conductor cell (see captions to Figures 12 and 14 for dimensions). The uncertainties shown are based on S-parameter and dimensional contributions. At 30 MHz electrode polarisation is expected to have a small but measurable effect (but no allowance for this is made in the evaluation of uncertainty). Further data for this sample are presented in Table 7 and Figure 17.

|            | 44-mm coaxial sensor |      |                |       | Discontinuous-inner-cond. cell |      |                |       |
|------------|----------------------|------|----------------|-------|--------------------------------|------|----------------|-------|
| Freq (MHz) | $\epsilon'$          | unc. | $\sigma$ (S/m) | unc.  | $\epsilon'$                    | unc. | $\sigma$ (S/m) | unc.  |
| 30         | 53                   | 1    | 0.726          | 0.008 | 54                             | 2    | 0.730          | 0.004 |
| 100        | 51                   | 1    | 0.745          | 0.008 | 51                             | 1    | 0.748          | 0.004 |
| 300        | 47                   | 1    | 0.838          | 0.009 | 47.2                           | 0.5  | 0.841          | 0.008 |

## 2.4 EXTRAPOLATION METHODS EVALUATED VIA STUDIES OF PERMITTIVITY AND CONDUCTIVITY DATA IN THE RANGE 1 MHz TO 350 MHz

There are two reasons why this report presents a method for extrapolation of permittivity and conductivity: (i) Measurements with coaxial sensors have a minimum frequency below which the uncertainty becomes too large (for a 44 mm sensor this is  $\approx 30$  MHz). (ii) Below a certain frequency, data for ionic samples obtained using any type of electroded probe is affected significantly by electrode polarisation (EP). Various schemes for reducing the effects of EP have been described (see page 4). For the measurements presented in this report EP is only significant at frequencies made below 50 MHz, so the suitability of extrapolations of measurements made at above 50 MHz to lower frequencies is discussed here.

NPL program *Qdfit* uses a NAG library routine [42] to fit complex permittivity data to an expression that approximately represents the frequency dependence of the complex permittivity of a sample. Real and imaginary components of  $\epsilon^*$  can be given by eqn. (2),

$$\epsilon' = a_0 + a_1 f + a_2 f^2 \quad (2a)$$

$$\epsilon'' = \sigma_i / (10^6 \omega \epsilon_0) + \Gamma_o f \quad (2b)$$

There are five real-valued parameters ( $a_0$ ,  $a_1$ ,  $a_2$ ,  $p$ ,  $\sigma_i$  and  $\Gamma_o$ ) that must be determined by fitting measured eqn. (2) to  $\epsilon^*$  data as a function of frequency. Note that  $f$  is the frequency in MHz, and  $\omega = 2\pi f$ . Typically, data obtained at frequencies from 50 MHz to 350 MHz is used. If it is assumed that EP is not significant in this range, the fitted parameters can then be used to calculate an extrapolated value for the ‘true’ permittivity and conductivity at lower frequencies. The rationale for eqn. (2) is as follows:

- The polynomial  $a_0 + a_1 f + a_2 f^2$  describes  $\epsilon'$  as a function of frequency. For water and saline  $a_1$  and  $a_2$  are expected to be small as the frequency of the first dielectric relaxation is so high (17 GHz for water at 20 °C). A second order (quadratic) function is sufficient to describe Tween-based phantoms (see Section 3) accurately in the 50 MHz to 350 MHz range. The validity of using the polynomial to extrapolate  $\epsilon'$  to lower frequencies depends on the type of the phantom and will be discussed in this section.
- The term  $\sigma_i / (10^6 \omega \epsilon_0)$  describes the frequency-behaviour of  $\epsilon''$ . This is the conventional relation for the effect of ionisation on the imaginary part of permittivity for ionic liquids applied when the ionic conductivity ( $\sigma_i$ ) is a real, frequency-independent quantity.
- The term  $\Gamma_o f$  describes an increase in  $\epsilon''$  which is caused by the ‘tail’ of a dielectric relaxation at GHz frequencies.

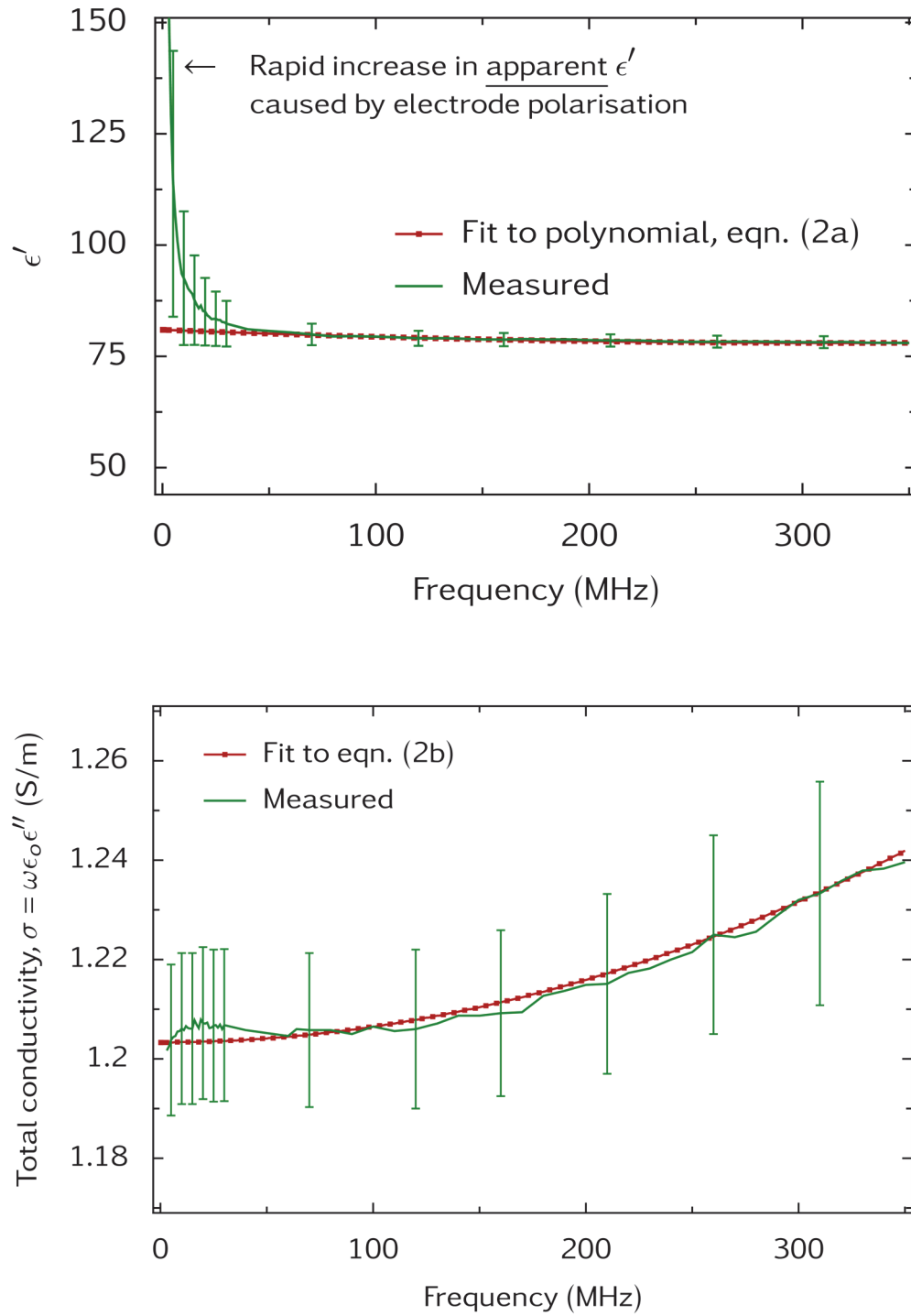


**Figure 15:** Measurements of the real part of permittivity (top graph) and the total conductivity of a conductivity reference standard liquid (Reagecon CSKC12880) at 22 °C made with a discontinuous-inner-conductor cell (green traces). A subset of the data (50 MHz to 350 MHz) was fitted to eqn. (2) – red traces show the fits. At the lowest frequencies electrode polarisation causes a large increase in the apparent permittivity. The static conductivity of the liquid is specified as  $1.215 \pm 0.012$  S/m at 22 °C. The dimensions of the cell are given in the caption to Figure 12. The evaluations of uncertainty do not account for electrode polarisation.

Parameters fitted to eqn. (2) were:  $a_0 = 80.97$ ,  $a_1 = -0.019 \text{ MHz}^{-1}$ ,  $a_2 = 2.9 \times 10^{-5} \text{ MHz}^{-2}$ ,  $\sigma = 1.203 \text{ S/m}$  and  $\Gamma_0 = 0.006 \text{ MHz}^{-1}$ .

### 2.4.1 Measurement of the conductivity of salt solutions

A discontinuous-inner conductor cell (Section 2.3) was used to measure a conductivity reference liquid (Reagecon CSKC12880) purchased from a chemical supplier. The liquid is an aqueous salt solution. A table of NIST-traceable data supplied with the liquid shows that the *static* conductivity  $\sigma$  is 1.288 S/m at 25 °C and 1.2153 S/m (tolerance  $\pm 1\%$ ) at 22 °C. Figure 15 (green traces) shows that a large increase in the apparent permittivity is observed at frequencies  $\gtrsim 30$  MHz. This change is described as ‘apparent’ as it is believed that it does not represent the actual behaviour of the sample, but to be due to EP. The size of EP effects increases for higher molar concentrations of dissolved salts. The apparent total conductivity is observed to be consistent with the static conductivity within the 5% tolerance required for SAR measurement throughout the measured range (up to 350 MHz).

For the Reagecon CSKC12880 sample, the measured permittivity is little affected by either EP or dielectric relaxation at frequencies in the range 50 MHz to 350 MHz. Data in this range was fitted to eqn. (2) (red traces). The ‘true’ permittivity and conductivity at frequencies below 50 MHz can be estimated by extrapolation; however for this liquid a measurement at e.g. 50 MHz only would often be sufficient. Thus it is possible to make measurements of the static conductivity of salt solutions traceable to RF impedance standards.

Similar behaviour would be expected for other low-frequency phantoms ( $\gtrsim 100$  MHz) based on salt solutions. To help establish that this is the case, tests on a sodium chloride solution (2.7g/l) that is used for MRI implant testing (Section 6) were made at 22 °C. By using the inductive conductivity meter (Figure 5) the static conductivity was found to be 0.47 S/m – see Table 5. Prior to this measurement the inductive conductivity meter was calibrated against the Reagecon CSKC12880 conductivity reference liquid referred to above. The calibration was checked using a conductivity reference liquid with conductivity nominally 0.5 S/m (Reagecon CSKC5M). The uncertainty of the measurement made using the inductive sensor is evaluated from the uncertainty associated with the specified static conductivity for the reference liquids, and the observed measurement non-repeatability. Table 5 also gives results obtained using the discontinuous-inner conductor cell (Figure 12) and the 44-mm coaxial sensor (Figure 8). These are seen to be in good agreement.

**Table 5:** Measurements on a saline (2.7g/l) phantom at 22 °C. †  
Saline phantoms with target conductivity  $\sigma = 0.47$  S/m are used for MRI implant testing – see Section 6. Uncertainties are shown for coverage factor  $k=2$ .

| Technique                                                       | 5 kHz        |      | 64 MHz      |              | 128 MHz |             |
|-----------------------------------------------------------------|--------------|------|-------------|--------------|---------|-------------|
|                                                                 | $\sigma$ S/m | unc. | $\epsilon'$ | $\sigma$ S/m | unc.    | $\epsilon'$ |
| 44-mm coaxial sensor †                                          |              |      | 79          | 1            | 0.488   | 0.005       |
| Discontinuous-inner-conductor cell *                            |              |      | 79          | 1            | 0.486   | 0.006       |
| Mettler-Toledo <i>Inpro 7250 ST</i> inductive probe and meter ‡ | 0.47         | 0.01 |             |              |         |             |

**Table 6:** Measurements on a PAA-Na + saline gel phantom at 22 °C (recipe from ASTM standard [30]).  
Gel phantoms with target conductivity  $\sigma = 0.47$  S/m are used for MRI implant testing – see Section 6. Uncertainties are shown for coverage factor  $k=2$ .

| Technique                                                       | 5 kHz        |      | 64 MHz      |              | 128 MHz |             |
|-----------------------------------------------------------------|--------------|------|-------------|--------------|---------|-------------|
|                                                                 | $\sigma$ S/m | unc. | $\epsilon'$ | $\sigma$ S/m | unc.    | $\epsilon'$ |
| 44-mm coaxial sensor †                                          |              |      | 88          | 1            | 0.503   | 0.006       |
| Discontinuous-inner-conductor cell *                            |              |      | 88          | 1            | 0.503   | 0.003       |
| Mettler-Toledo <i>Inpro 7250 ST</i> inductive probe and meter ‡ | 0.49         | 0.02 |             |              |         |             |

**Table 7:** Measurements on a head phantom based on polysorbate 20 at 22 °C. The phantom is formulated to achieve  $\sigma = 0.76$  S/m at 150 MHz, but has a wide usable bandwidth – see Section 4.2. Uncertainties are shown for coverage factor  $k=2$ .

| Technique                                                       | 5 kHz        |      | 64 MHz      |              | 128 MHz |             |
|-----------------------------------------------------------------|--------------|------|-------------|--------------|---------|-------------|
|                                                                 | $\sigma$ S/m | unc. | $\epsilon'$ | $\sigma$ S/m | unc.    | $\epsilon'$ |
| 44-mm coaxial sensor †                                          |              |      | 52          | 1            | 0.734   | 0.008       |
| Discontinuous-inner-conductor cell *                            |              |      | 52          | 1            | 0.738   | 0.004       |
| Mettler-Toledo <i>Inpro 7250 ST</i> inductive probe and meter ‡ | 0.71         | 0.02 |             |              |         |             |

‡ The ASTM standard [30] currently specifies a saline phantom that has a lower salt concentration (2.5g/l) and achieves  $\sigma = 0.47$  S/m (at 64 MHz) at approximately 26 °C.  
† 44-mm sensor used with cavity (as shown in Figure 8). Water was used as the calibration reference liquid.

\* Cell dimensions as given in the caption to Figure 12.

‡ Conductivity meter calibrated against standard solution with static conductivity 1.288 S/m at 25°C (data is supplied for a range of temperatures).  
Inductive probe measurements are more repeatable for low viscosity samples, e.g. saline, as samples are more uniform and are free from bubbles.

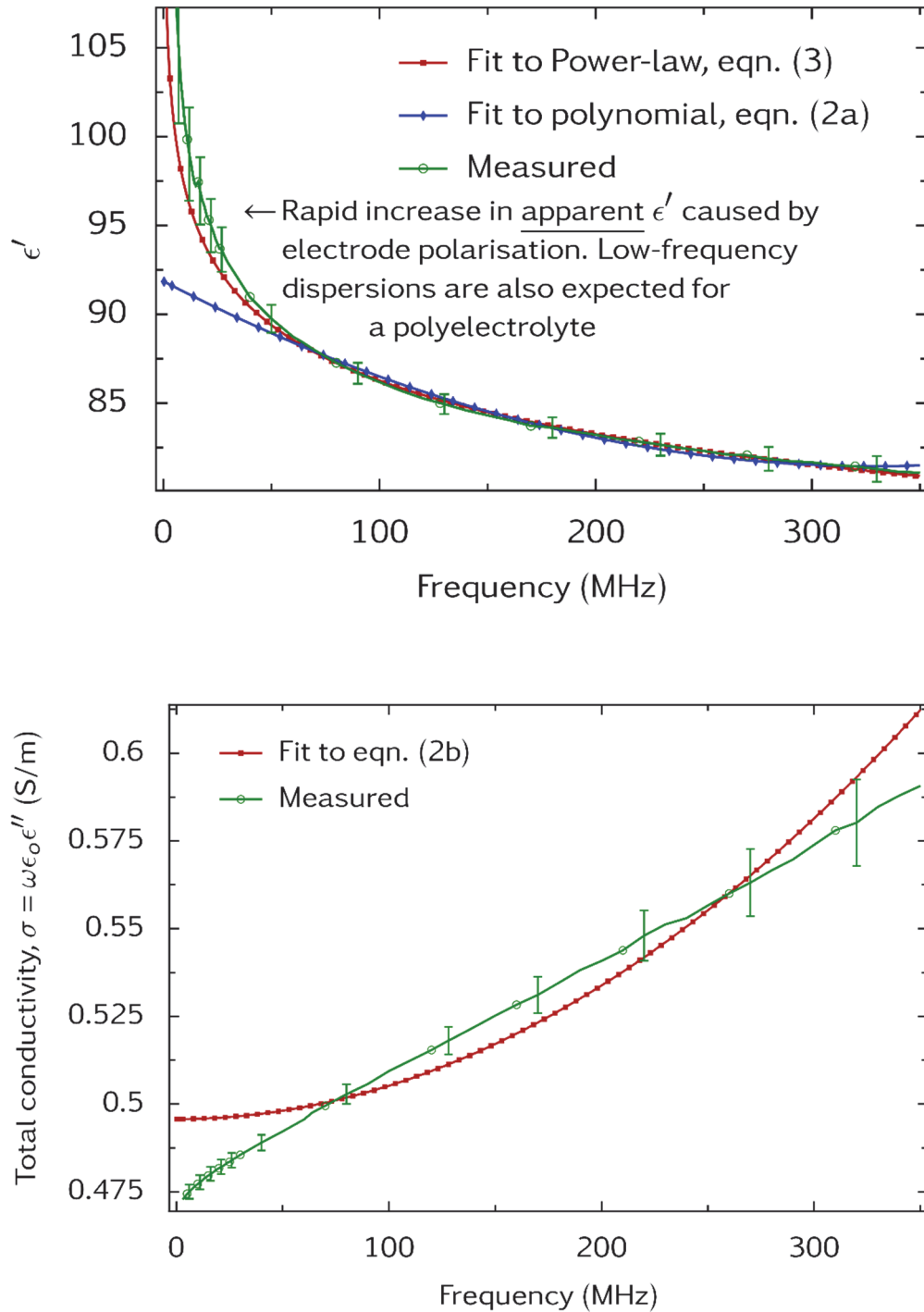


**Figure 16:** Measurements of the real part of permittivity (top graph) and the total conductivity of a gel phantom at 22 °C made with a discontinuous-inner-conductor cell. This type of phantom is used for MRI implant testing (see Section 6). It contains long-chain polymer molecules (polyacrylic acid partial sodium salt) so dielectric dispersions at kHz and MHz frequencies are expected to occur (see text). A subset of the data (50 MHz to 350 MHz) was fitted to eqn. (2) – red traces show the fits. The blue trace on the  $\epsilon'$  plot was calculated from a fit a power law, eqn. (3). The increase in apparent permittivity at frequencies below 50 MHz is interpreted as being due to a combination of electrode polarisation and low-frequency dispersions. The static conductivity recorded using a calibrated inductive probe was 0.48 S/m at 22 °C. The dimensions of the discontinuous-inner-conductor cell are given in the caption to Figure 12. The evaluations of uncertainty do not account for electrode polarisation.

### 2.4.2 Measurements on a phantom liquid that contains a polymer-based gelling agent

For phantom liquids that contain organic chemicals, relaxation phenomena are expected to occur at lower frequencies than for salt solutions, in which case the actual permittivity and total conductivity may vary significantly in the 50 MHz to 350 MHz range. This is particularly likely to be the case for the phantom investigated here, which is based on polyacrylic acid partial sodium salt (PAA-Na) – a polymer with macromolecules that contain many thousands of repeating units. When the PAA-Na is dissolved in water a gel is formed. The required conductivity is obtained by the addition of NaCl. Gel phantoms are advantageous for thermal measurement of SAR, as convective transport of heat is reduced (see Section 6). The recipe used is designed for assessing the risk associated with bio-implants for patients undergoing MRI (see Section 6).

Measurements on a sample of a gel phantom (contains PAA-Na) formulated according to the recipe specified by the ASTM standard [30] for MRI medical-implant testing were made with the discontinuous-inner conductor cell. They are plotted in Figure 16 and tabulated in Table 6. Measurements on the same sample obtained by using a 44-mm coaxial sensor (which are seen to be in excellent agreement) are also tabulated in Table 6. The measured static conductivity is observed to be lower than the RF conductivity by 7% at 128 MHz. If the formulation was adjusted to give a slightly lower static conductivity (e.g. 0.45 S/m), the RF conductivity should be well within the specification [30] ( $0.47 \text{ S/m} \pm 10\%$ ) at both 64 MHz and 128 MHz at 22 °C. The repeatability of measurements made using the inductive probe is worse for a gel than for a salt solution (Table 5) so the overall uncertainty is increased.

A macromolecule that has ionisable groups along its length is classed as a polyelectrolyte. The dielectric spectra of polyelectrolytes dissolved in water is noted to be very complex [15] – with dielectric dispersions typically between 1 and 100 kHz, 1 and 500 MHz, and above 10 GHz. The problem in analysing the observed responses is how to differentiate electrode polarisation effects and the ‘intrinsic’ dielectric relaxation behaviour. The shape of the measured  $\epsilon'$  spectrum of the gel phantom (Figure 16) differs markedly from that of a salt solution (Figure 15), which appears to confirm that dielectric dispersion phenomena occur at frequencies below 10 MHz (in addition to the expected EP at frequencies below  $\approx 50$  MHz). A power-law eqn. (3), in which  $A$  and  $p$  are fitted real parameters, is observed to be a better fit to the permittivity than the polynomial, eqn. (2a), and seems to provide a more plausible extrapolation to frequencies below 50 MHz. These measurements, however, do not provide conclusive evidence that effects of EP can be ‘removed’ by a power-law extrapolation.

$$\epsilon' = A/\omega^p \quad (3)$$

### 2.4.3 Measurements on a polysorbate-based phantom

Measurements on 0.15 GHz head phantom (which is based on polysorbate 20 – see Table 9) are presented in Table 7 and plotted in Figure 17. While the permittivity is lower, the plotted traces have a very similar shape to those of the salt solution (Figure 15), e.g. EP effects cause an increase in apparent permittivity is observed at frequencies below 50 MHz. Static conductivity and RF conductivity are observed to be consistent to within 5% at frequencies up to 100 MHz. At 150 MHz, the RF conductivity is approximately 7% higher than the static conductivity. The permittivity and conductivity have a more marked frequency dependence in the measured range than they do for the salt solution. The most likely reason for is that the frequency of the first relaxation of the polysorbate phantom is lower.

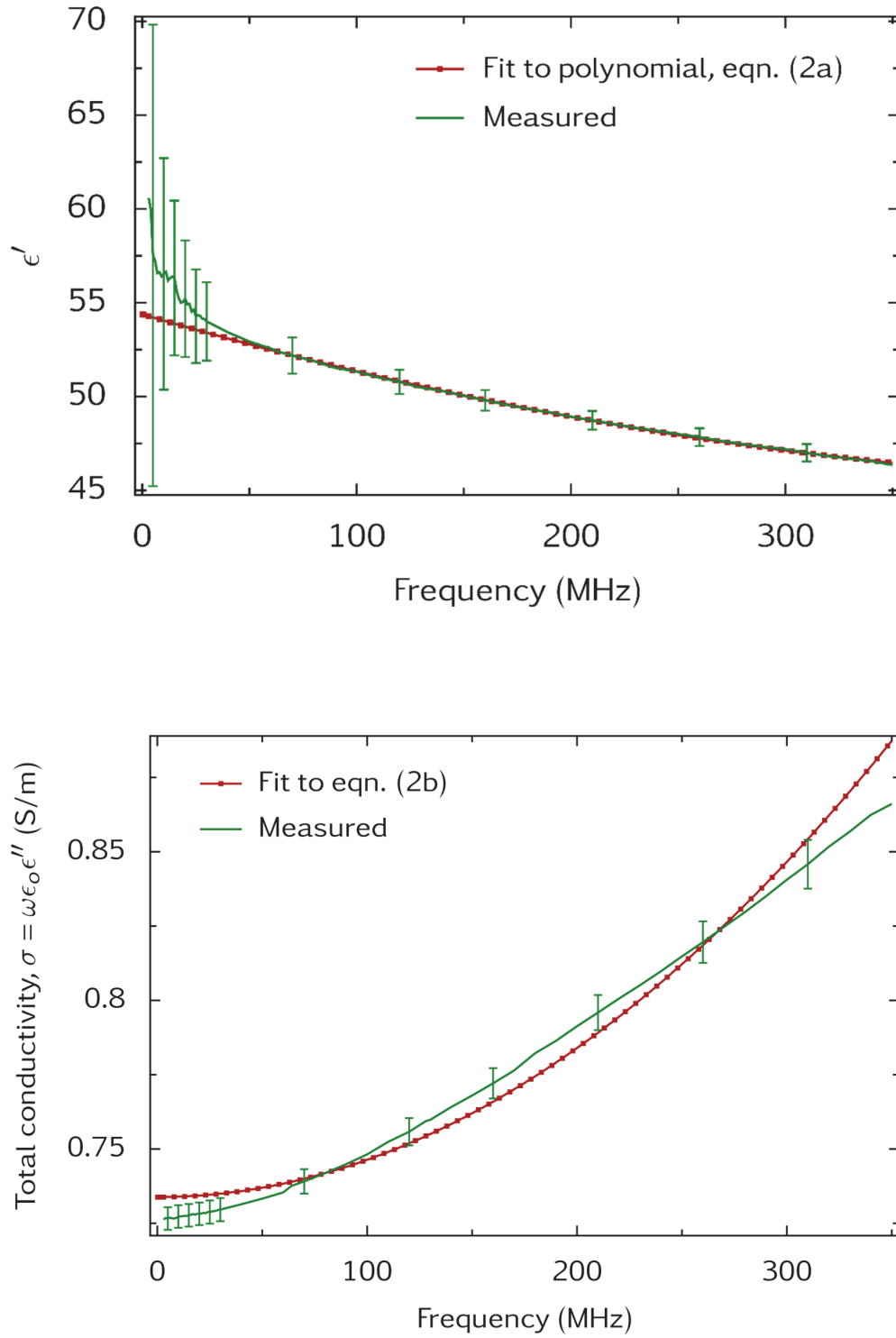


**Figure 17:** Measurements of the real part of permittivity (top graph) and the total conductivity of 0.15 GHz head phantom at 22 °C made with the discontinuous-inner-conductor cell. A subset of the data (50 MHz to 350 MHz) was fitted to eqn. (2) – red traces show the fits. The dimensions of the cell are given in the caption to Figure 12. The evaluations of uncertainty do not account for electrode polarisation. The phantom is based on polysorbate 20 – see Table 9 for recipe.

#### 2.4.4 Electrode polarisation compared for a coaxial cell and a coaxial sensor

Figure 18 shows measurements on the polysorbate 0.15 GHz head phantom that were made by using the discontinuous-inner-conductor cell (Figure 12), and the 44 mm coaxial sensor with cylindrical cavity (Figure 9). Data presented in Figure 17, and Tables 4 and 7, are from the same actual measurements. For both instruments, the calibrations were shown to be accurate throughout the measured frequency range (3 MHz to 350 MHz) by making ‘check’ measurements on reference liquids. The measurements on the phantom agree well at frequencies above 30 MHz, but the coaxial sensor measurement at lower frequencies shows a much larger error due to EP. This is almost certainly a real trend although the evaluated uncertainties for both methods are large at the lowest frequencies. The difference in the shape of the observed responses is believed to occur because of differences in electrode materials and their surface finishes; the coaxial sensor is aluminium and the coaxial cell is gold-flashed brass (outer conductor) and stainless steel (inner conductor). Results such as these demonstrate why reliable corrections for EP are not easily made.

#### 2.5 CALIBRATION REFERENCE DATA FOR DIELECTRIC MEASUREMENT IN THE 5 GHz TO 10 GHz RANGE

The frequency range for which SAR measurements is specified usually extends to 6 GHz (at higher frequencies exposure limits are specified in terms of power flux density, as the penetration depth of fields into the body becomes very small). However, ICNIRP [1] gives SAR as the basic human restriction for EMF exposure up to 10 GHz, so as part of this work dielectric measurement and recipes for phantoms at frequencies in the range 6 GHz to 10 GHz are also considered. One aspect of this that must be considered is the availability of traceable data for calibration and ‘check’ reference liquids used for calibrating coaxial sensors.

NPL report MAT 23 [14] gives traceable complex permittivity for a number of polar liquids at frequencies up to 5 GHz. Two experimental approaches were employed to demonstrate that the data for methanol, ethanediol and DMSO can be extrapolated up to 10 GHz with reasonable accuracy using relaxation parameters fitted to single-relaxation models [12]. However, full traceability to impedance standards cannot be claimed for extrapolated reference data as it is not necessarily the case that the relaxation behaviour is as predicted.

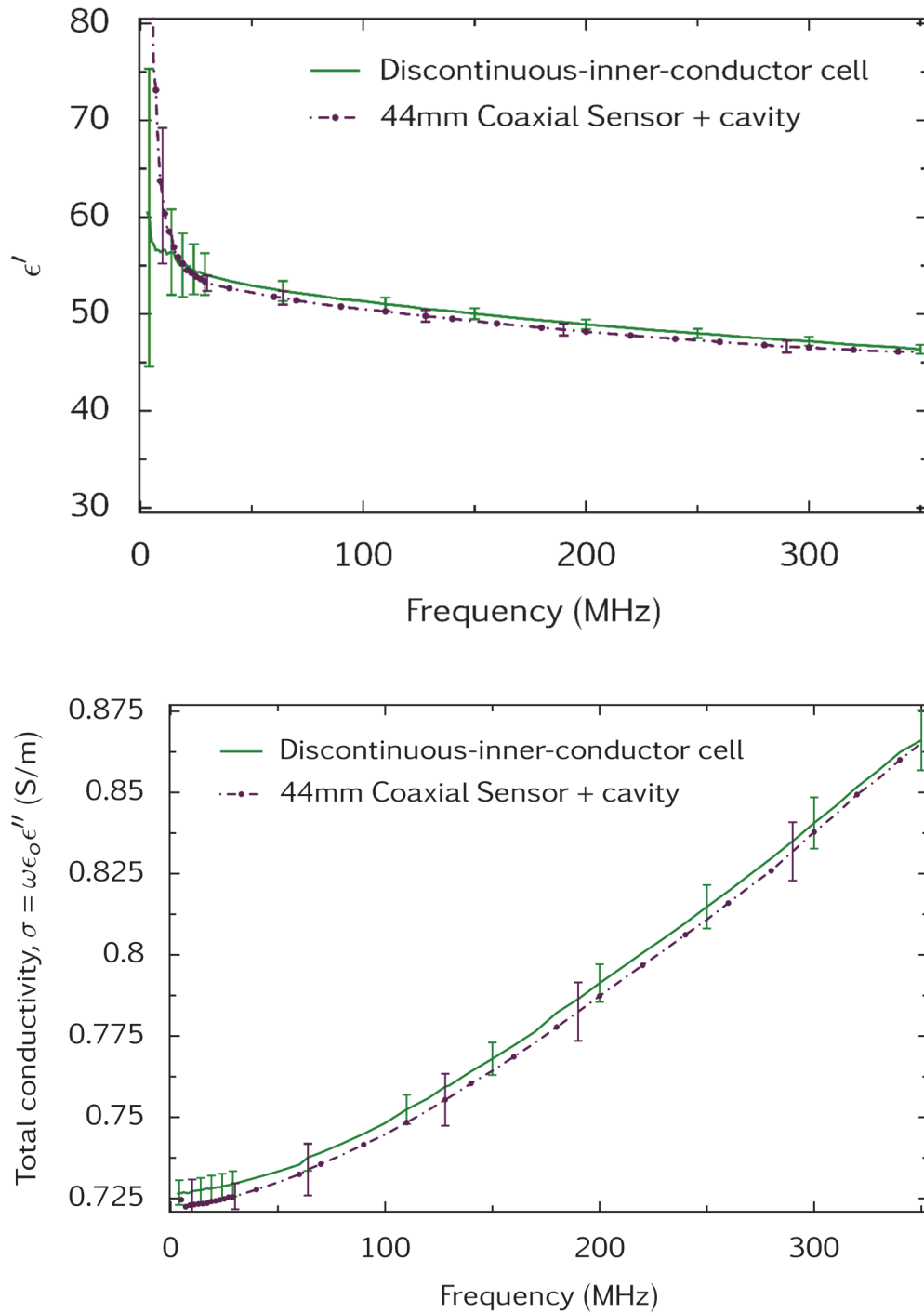


**Figure 18:** Measurements of the real part of permittivity (top graph) and the total conductivity of 0.15 GHz head phantom made with two different instruments: A 44-mm coaxial sensor (with cylindrical cavity) and a discontinuous-inner-conductor cell (dimensions given in the captions to Figures 8 and 12). Electrode polarisation is observed to have a markedly different effect on the measured permittivity for the two cells at frequencies below 30 MHz. The discontinuous-inner-conductor cell data is the same as that plotted in Figure 17. Data at 64 MHz and 128 MHz is tabulated in Table 7. The measurements were made at 22 °C. The evaluations of uncertainty do not account for electrode polarisation. The phantom is based on polysorbate 20 – see Table 9 for recipe.

### 2.5.1 Tests with a coaxial sensor

A 7-mm coaxial sensor was calibrated at frequencies up to 10 GHz using a least squares method [35] in which methanol, ethanediol and DMSO were used as reference liquids. When an over-defined calibration scheme is used the measured reflection coefficient ( $S_{11}$ ) residual calibration errors [35] can be used to assess the consistency of the definitions of the calibration artefacts – which for liquids is a test of how accurately the complex permittivity is known. All of these liquids have comparatively high relaxation frequencies, and so it is expected that the single-relaxation models used might have sufficient accuracy up to at least 10 GHz. Figure 19 shows that the residual errors do not change substantially at frequencies up to 10 GHz, so this is demonstrated to be the case.

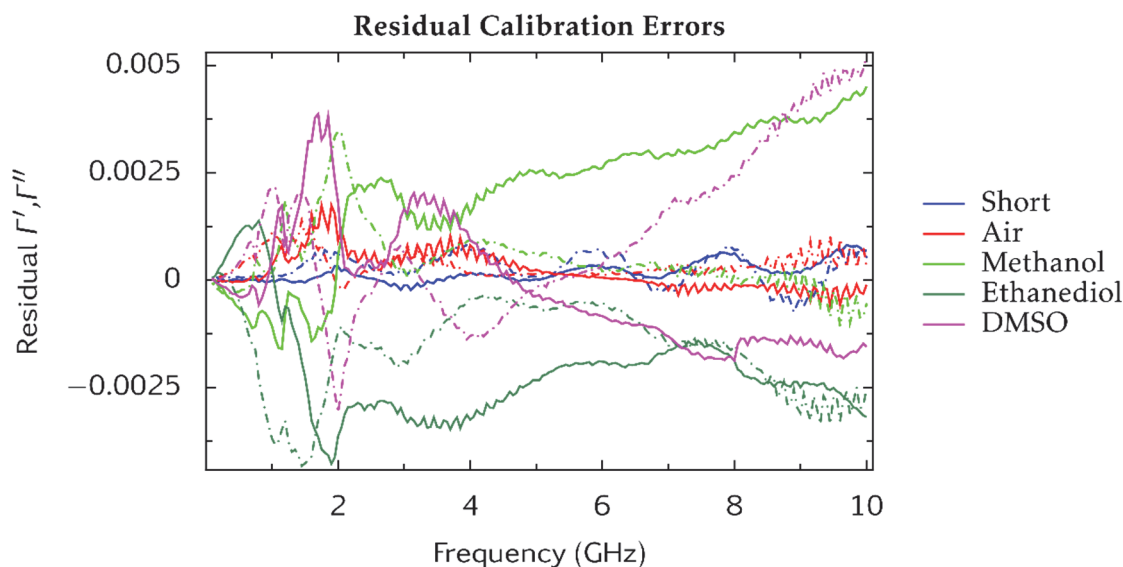


**Figure 19:** Real (solid lines) and imaginary (broken lines) residual calibration errors for a 7-mm coaxial sensor. The peaks at frequencies below 2 GHz flange resonances may be associated with flange resonances [35]. They do not occur at higher frequencies as the loss tangent of the liquids is higher. The graph shows that if only one of the liquids were used for calibration, then measurements on the other two liquids would be consistent with the MAT 23 [14] data extrapolated up to 10 GHz.

### 2.5.2 Tests with a waveguide transmission system

Measurements were undertaken using a waveguide transmission system based on WG16 (Figure 20) calibrated by using the TRL method. The nominal frequency range for WG16 is 8.2 GHz to 12.4 GHz. A waveguide spacer 5-mm in length is used to contain the liquid samples. A comprehensive uncertainty evaluation was performed. There were some technical problems with this experiment such as a tendency for leakage to occur at the dielectric inserts. Preventing such leakage is found to be more difficult for rectangular inserts than for cylindrical ones used in coaxial measurement cells [40].

Measurements using the WG16 cell for water, methanol, DMSO and ethanediol at 20 °C are shown in Table 8. These provide further evidence that the single-relaxation models used are accurate up to 10 GHz. It might be noted that uncertainties are larger than those obtained at lower frequencies using coaxial cells [14, 40]. Table 8 also includes reference data for these liquids extrapolated to 10 GHz.

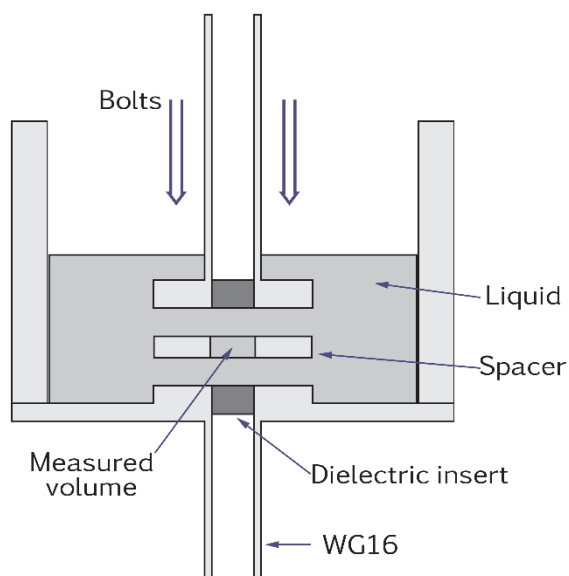


**Figure 20:** NPL WG16 transmission system for measurements on reference liquids.

**Table 8:** Measurements of complex permittivity for various liquids (all at 20 °C) at 10 GHz in WG16 system employing a measurement cell of 5-mm length. Leakage at the dielectric inserts was a particular problem for methanol, and the possibility of an error in the measurement cannot be excluded.

| Liquid     | Measured |      |      |      | Reference data    |      |                   |      |
|------------|----------|------|------|------|-------------------|------|-------------------|------|
|            | Re       | unc. | Im   | unc. | Re                | unc. | Im                | unc. |
| Methanol   | 7.8      | 0.4  | 7.6  | 0.3  | <sup>a</sup> 7.72 | 0.11 | <sup>a</sup> 7.32 | 0.06 |
| DMSO       | 21.1     | 0.7  | 19.5 | 0.5  | <sup>a</sup> 21.5 | 0.1  | <sup>a</sup> 19.4 | 0.4  |
| Ethenediol | 6.1      | 0.2  | 5.0  | 0.2  | <sup>a</sup> 6.3  | 0.1  | <sup>a</sup> 4.8  | 0.1  |
| Water      | 60.5     | 2.5  | 32.4 | 1.1  | <sup>b</sup> 61.0 | 0.4  | <sup>b</sup> 32.6 | 0.3  |

<sup>a</sup> Extrapolated to 10 GHz from MAT 23 [14]. The uncertainties shown are obtained from look-up tables which were obtained by Monte-Carlo modelling [40]. Software (*Qmat23*) was used for interpolating the reference data.

<sup>b</sup> Computed using data from Kaatze [13]. Kaatze's uncertainties are assumed to be standard uncertainties and here are expanded to  $k=2$ . The uncertainties are computed from the published uncertainties in the Debye parameters by using the law of propagation of uncertainty. Co-variances between the uncertainties of Debye parameters may exist. These are not accounted for by this approach.

### 3 OVERVIEW OF SPECIFICATION AND FORMULATION OF PHANTOMS

International standards for the assessment of SAR [4-6, 43] give agreed values for permittivity of head and body tissue as a function of frequency which are used as ‘target’ values for tissue-equivalent materials (phantoms). These are based on the human tissue data published by Gabriel [7]. According to the standards [4-5], traceable measurement of SAR requires that the complex permittivity is within 10% of that specified. A number of recipes for phantoms based have been proposed. Exact agreement with the specified values of complex permittivity can be achieved at a single frequency by adjustment of the proportions of constituents. However, recipes for phantoms that accurately reproduce the target values for the complex permittivity of tissues over a broad range of frequency are not easily devised. Tissue contains free and bound water, as well polarisable structures such as cell membranes and proteinaceous material. Dielectric spectroscopy shows that there are multiple processes; in references [15, 29, 44-46]  $\alpha$ ,  $\beta$  and  $\gamma$  dispersions are described. The  $\alpha$  dispersion occurs at Hz – kHz frequencies and is reported to be associated with diffusion of counterions that build-up across cell membranes [45]. Unlike EP,  $\alpha$  dispersion is not an artefact of measurement, but reflects the true properties of the tissue. Knowing how to interpret measurements on tissue made with electroded systems at kHz frequencies and lower is a longstanding problem; EP and  $\alpha$  dispersions both cause the observed  $\epsilon'$  to increase by orders of magnitude, but a clear distinction between them is not easily made [15]. Many publications report permittivity measurements for tissue that are of the order of  $10^7$  at 1 kHz. Inhomogeneous media often show dispersions caused by the Maxwell Wagner effect as a result of *interfacial polarisation*. These are the cause of  $\beta$  dispersions which for tissue occur at frequencies of the order of 10 – 100 MHz. Relaxation behaviour at frequencies of approximately 20 GHz (corresponding to Debye relaxation in water) is the cause of  $\gamma$  dispersions. Homogeneous phantoms that match the properties tissue can only be made at frequencies above approximately 30 MHz (depending on the type of tissue).

The General requirements for phantoms can be summarised as follows:

- Temperature coefficient of the complex permittivity below 5% per °C.
- Stable over long periods of time (at least six months).
- Does not corrode or attack probe, containers etc., and leaves them easy to clean,
- Nontoxic and low odour.
- Complex permittivity within 10% that specified at the measurement frequencies.

For liquid phantoms that allow electric field probes to be scanned within them there are two further requirements:

- Low viscosity.
- Visibly transparent for systems that use an optical proximity sensor to avoid collisions between probes and the phantom shell.

This report gives recipes for non-toxic head and body liquid phantoms based on *polysorbate 20*, *polysorbate 80*, and *polysorbate 85* (tradenames Tween 20, Tween 80 and Tween 85) mixed with water and salt for frequencies between 30 MHz and 10 GHz. These phantoms meet all of the requirements listed above. They are suitable for use with commercial SAR measurement systems. The complex permittivity of 30 MHz to 6 GHz recipes has been observed to be stable for periods of up to six years.

Target properties for 6 GHz to 10 GHz, which are not currently available in the standards, are also derived in this report. It is demonstrated that measurements of SAR using phantoms with these properties are conservative, i.e. the indicated SAR is more likely to be above rather than below the SAR that would be obtained in a human head.

The permittivity of human tissues at frequencies below  $\approx 30$  MHz is observed to be above that of water [29, 47-48] and cannot be matched by any of recipes for liquid and gel phantoms that are commonly used. So target permittivity values that are lower than those of actual tissue are adopted. Target conductivity values can, however, be attained by e.g. adjusting the concentration of the salt component of the mixes. None of the current standards specifies target properties for the frequency range 1 MHz to 30 MHz, but the next version of IEC 62209 (in preparation) may make recommendations for the band 10 MHz to 30 MHz. This report proposes target values and a recipe suitable for measurement of induced current and whole-body SAR for the 1 MHz to 30 MHz range (see Section 7.1).

At specific frequencies below 100 MHz tissue permittivity values (or target values) that have a value of 75 to 80 can be identified from Figures 21 and 22. This corresponds to the typical permittivity of salt solutions [28] so it is possible to make a simple phantom these specific frequencies by controlling the amount of salt to achieve the required conductivity. Therefore salt solutions can be used as phantoms, but with limited flexibility as an arbitrary permittivity cannot be achieved. Salt solutions are binary recipes without organic constituents that might degenerate, so for long-term monitoring, measurement of conductivity only with a conductivity meter may be sufficient. The evidence presented in Section 2.4 would suggest that it would be legitimate to use a value of static conductivity measured e.g. with a kHz conductivity probe (see Section 2.1.2). Prolonged contact between salt solutions and exposed copper or brass will result in corrosion, which may be a limitation in some experiments.

An additional requirement not discussed above is for high-viscosity phantoms for measurement of localised SAR or localised temperature rises, e.g. for MRI implant testing (Section 6). It is necessary to use a high viscosity phantom to limit error caused by thermal convection [49].

### 3.1 SPECIFICATIONS FOR PHANTOMS IN CURRENT STANDARDS

The target properties for these phantoms are specified in standards for the measurement of SAR [4-6, 43]. FCC OET65 specifies both head and body phantoms for 150 MHz to 6 GHz [6]. The IEC-62209 standards [4-5] specify head phantoms for testing both head and body mounted devices, as this reduces the number of phantoms required. The rationale for this is that the head phantom should yield an over-estimate of the body SAR due to the lower real part of the permittivity.

Figure 21 shows the real part of the permittivity and conductivity for brain grey matter and white matter, together with the target values from IEC62209-2, which correspond to those in IEEE 1528 [43]. It can be seen that the target permittivity closely matches that of brain white matter, and the target conductivity closely matches that of brain grey matter. This is because lower permittivity and higher conductivity will yield higher SAR, so that the phantom will be conservative for head SAR in most cases. Figure 22 shows the tissue real part of the permittivity and conductivity for muscle and also the phantom target values from FCC-OET65 [6]. The real part of the permittivity specified for the body phantom matches that of muscle, and the conductivity is about ten percent higher than that of muscle, which ensures that the phantom will give a conservative estimate for SAR.

Recent versions of standards have increased the frequency range for which SAR measurement is specified, which has led to the requirement for new phantoms. The latest IEC-62209-2 (body mounted devices) draft [5] has extended the lower frequency limit from 300 MHz down to 30 MHz, so that this standard now covers 30 MHz to 6 GHz. The upper frequency limit of IEEE 1528 for head mounted devices [43] has been increased from 3 GHz to 6 GHz. Figure 21 shows that for 30 MHz, the target real part of the permittivity is lower than that of brain because the tissue permittivity is too high to be achieved using a simple liquid, as required for the SAR testing.

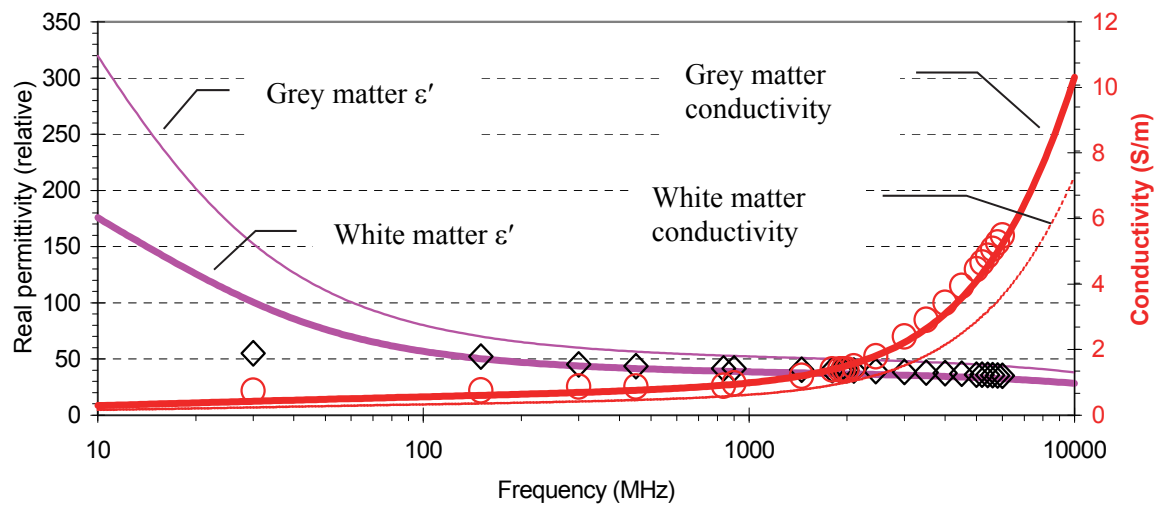


**Figure 21:** Real part of the permittivity and conductivity of brain grey matter and white matter from Gabriel [7]. Target values from IEC62209-2 standard [5] shown as diamonds (real part of the permittivity) and circles (conductivity). The target values for real part of the permittivity closely match those of white matter at frequencies above 100 MHz, and conductivity matches that of grey matter. Below 100 MHz a permittivity of 50 is used.

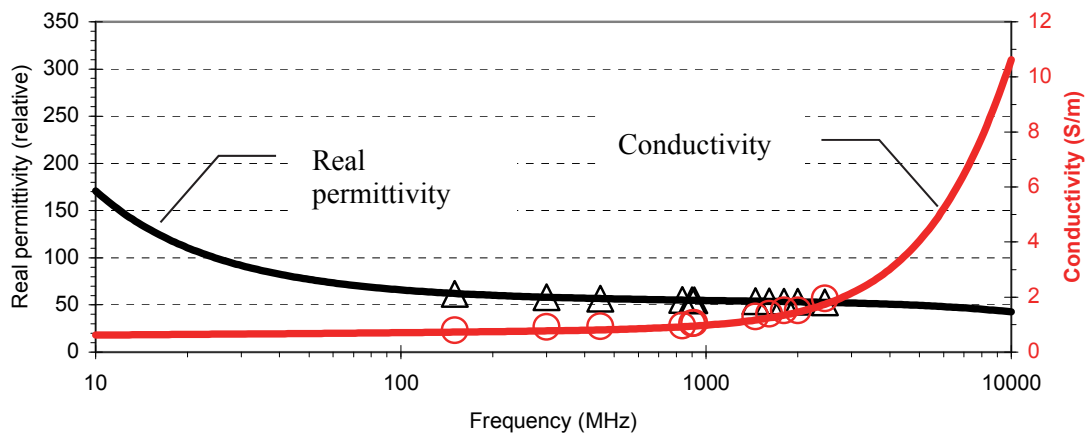


**Figure 22:** Showing the real part of the permittivity and conductivity of muscle (from Gabriel) and also the target values specified by the Federal Communications Commission (FCC) [6] (circles for conductivity, triangles for real part of the permittivity). The target values for permittivity match those of muscle, and the target conductivity is about 10% higher than that of muscle.

In the IEC and IEEE standards [4-5, 43], the required tolerance of the permittivity and conductivity of phantoms is  $\pm 10\%$  at all frequencies. A formula has been provided to correct the measured value of SAR for the deviation of the phantom permittivity and conductivity from the target values. This makes it easier to achieve the required values, and increases the usable bandwidth of the phantoms without significantly increasing the SAR measurement uncertainties. In previous versions of IEEE 1528, the specified tolerance of the measured real part of the permittivity and conductivity was  $\pm 5\%$  of the target values, except for frequencies of 5 GHz to 6 GHz where a  $\pm 10\%$  tolerance was allowed (it is more difficult to achieve the correct values of permittivity and conductivity in this frequency range). The properties of phantoms change with time due to evaporation, so permitting greater tolerances increases their longevity. The greater tolerance implies that the frequency range of phantom liquids is increased which, if SAR measurements at multiple frequencies are needed, reduces the number of phantoms that must be maintained.

For frequencies above 1450 MHz, some of the phantoms specified in IEEE 1528 contain Diethylene Glycol Butyl Ether (DGBE), which is hazardous and environmentally damaging. For frequencies of 900 MHz and below sucrose solutions are specified. These are harmless, but are viscous and can be difficult to clean off equipment.

## **4 POLYSORBATE-BASED RECIPES FOR THE FREQUENCY RANGE 30 MHz TO 6 GHz**

### **4.1 PHANTOM RECIPES AND MIXING INSTRUCTIONS**

This section gives recipes for non-toxic head and body phantoms based on polysorbate 20 or polysorbate 80 mixed with deionised water and salt for frequencies between 30 MHz and 6 GHz, as required for measuring SAR of RF energy in the body arising from transmitters. These phantoms have been developed as a collaboration between NPL and University of Bristol over a number of years and have been published previously [50]. The phantoms are translucent, have low viscosity and low temperature coefficients, and were found to have stable complex permittivity for periods up to six years, making them suitable for use with commercial SAR measurement systems. They are non-toxic and are not environmentally damaging. Table 9 gives the percentage (by weight) of each of the ingredients to achieve the target properties specified in standards [5-6] at a temperature of 22 °C. The material supplier details are given in Appendix 1.

#### **4.1.1 The mixing procedure**

The salt (if required) is dissolved in the deionised water (stirring using a magnetic or overhead stirrer). The water salt mix is then added to the required polysorbate and mixed thoroughly. It is important that the mixture is not heated during mixing, as this can irreversibly change the properties of polysorbate. A small amount (e.g. 0.3% by weight) of a suitable bactericide may be added to the final mix to prevent moulds etc. growing. This has little effect on the dielectric properties of the phantom.

### **4.2 USABLE BANDWIDTH OF THE PHANTOMS**

Figure 23 shows the frequency range over which both the conductivity and real part of the permittivity of the head phantoms in Table 9 are within  $\pm 5\%$  and  $\pm 10\%$  of the target values

specified in [5-6] for both conductivity and real part of the permittivity as this determines their usable frequency range. A  $\pm 10\%$  tolerance is achieved from 30 MHz to 450 MHz with one phantom (three are required for  $\pm 5\%$  tolerance) and from 1.95 GHz to 6 GHz with two phantoms (six are required for a  $\pm 5\%$  tolerance), indicating the benefit of relaxing the required tolerance of the phantom.

Figure 24 shows the variation of the conductivity with frequency for the 150 MHz head phantom. Figure 25 shows the corresponding variation in the real part of the permittivity. This phantom is based on polysorbate 20. The graphs also show the  $\pm 10\%$  tolerance limits of the target values. In this case, the frequency response of the real part of the permittivity of the phantom closely matches that of the target values, but the conductivity does not. The phantom is within the  $\pm 10\%$  tolerance from 30 MHz to 450 MHz (note that 3 phantoms would be required to achieve a  $\pm 5\%$  tolerance in this frequency range).

Figures 26 and 27 show the frequency response of the 5 GHz to 6 GHz head phantom, which is based on polysorbate 80. In this case the conductivity closely matches the frequency response of the target values, whilst the real part of the permittivity does not. Using polysorbate 80 for the phantoms between 1.9 GHz and 6 GHz would achieve broader bandwidths than those based on polysorbate 20, although it is worth noting that the polysorbate 80 is more expensive and also more difficult to mix than polysorbate 20.

**Table 9:** Recipes for head and body phantoms

| Phantom            |      | Target properties,<br>from [5-6] |                 | Ingredients, by weight |                          |                          |             |
|--------------------|------|----------------------------------|-----------------|------------------------|--------------------------|--------------------------|-------------|
| Frequency<br>(GHz) | Type | $\epsilon'$                      | $\sigma$<br>S/m | Water<br>%             | Polysorbate<br>20<br>(%) | Polysorbate<br>80<br>(%) | NaCL<br>(%) |
| 0.03               | Head | 55.0                             | 0.75            | 50.43                  | 47.37                    | 0                        | 2.19        |
| 0.15               | Head | 52.3                             | 0.76            | 53.03                  | 45.17                    | 0                        | 1.79        |
| 0.30               | Head | 45.3                             | 0.87            | 50.43                  | 47.37                    | 0                        | 2.19        |
| 0.45               | Head | 43.5                             | 0.87            | 50.81                  | 47.59                    | 0                        | 1.60        |
| 0.90               | Head | 41.5                             | 0.97            | 52.87                  | 46.10                    | 0                        | 1.03        |
| 1.80               | Head | 40.0                             | 1.40            | 55.40                  | 44.22                    | 0                        | 0.38        |
| 1.90               | Head | 40.0                             | 1.40            | 55.24                  | 44.57                    | 0                        | 0.19        |
| 2.45               | Head | 39.2                             | 1.80            | 55.75                  | 45.25                    | 0                        | 0.00        |
| 3.50               | Head | 37.9*                            | 2.92*           | 57.95                  | 61.95                    | 0                        | 0.1         |
| 5.80               | Head | 35.3                             | 5.27            | 62.70                  | 0.00                     | 37.30                    | 0.00        |
|                    |      |                                  |                 |                        |                          |                          |             |
| 0.15               | Body | 61.9                             | 0.81            | 70.73                  | 28.33                    | 0                        | 0.93        |
| 0.30               | Body | 58.2                             | 0.92            | 70.32                  | 28.70                    | 0                        | 0.98        |
| 0.45               | Body | 56.7                             | 0.94            | 71.10                  | 28.00                    | 0                        | 0.90        |
| 0.90               | Body | 55.0                             | 1.05            | 71.30                  | 28.00                    | 0                        | 0.70        |
| 1.80               | Body | 53.3                             | 1.52            | 71.50                  | 28.00                    | 0                        | 0.50        |
| 1.90               | Body | 53.3                             | 1.52            | 71.61                  | 28.00                    | 0                        | 0.39        |
| 2.45               | Body | 52.7                             | 1.95            | 71.70                  | 28.00                    | 0                        | 0.30        |
| 5.80               | Body | 48.2                             | 6.00            | 80.00                  | 0.00                     | 20.0                     | 0.00        |

\*These values are obtained by linear interpolation.

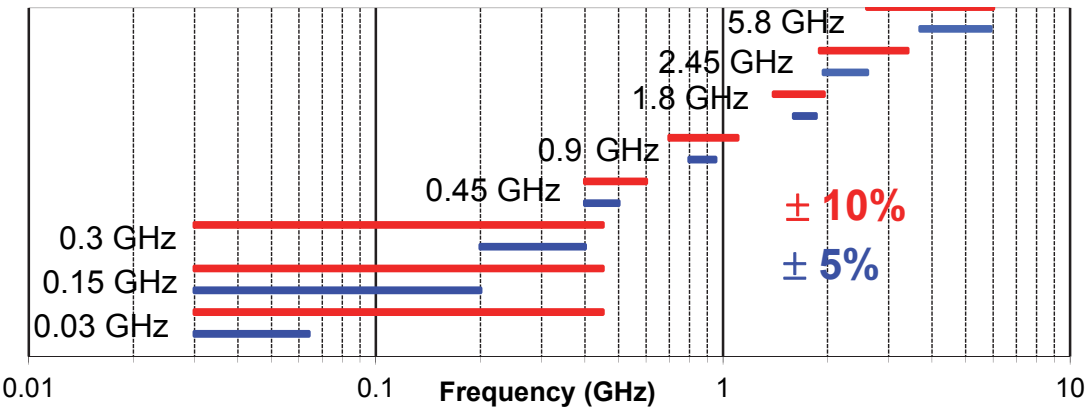


**Figure 23:** The frequency range over which the head phantoms shown in Table 9 are within specification to:  $\pm 5\%$  (blue lines) and  $\pm 10\%$  (red lines). Relaxing the tolerance approximately doubles the usable bandwidths of the phantoms.

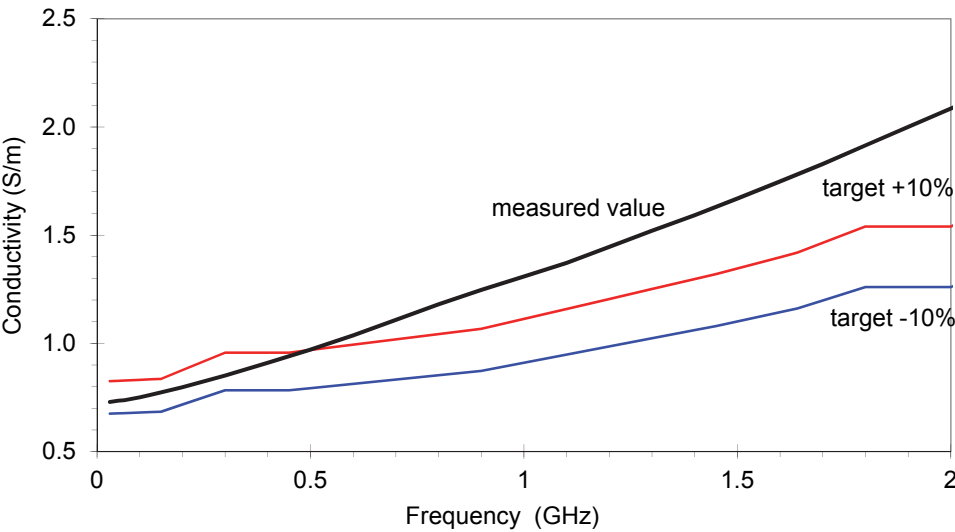


**Figure 24:** Conductivity versus frequency for 0.15 GHz head phantom permittivity at 22 °C.

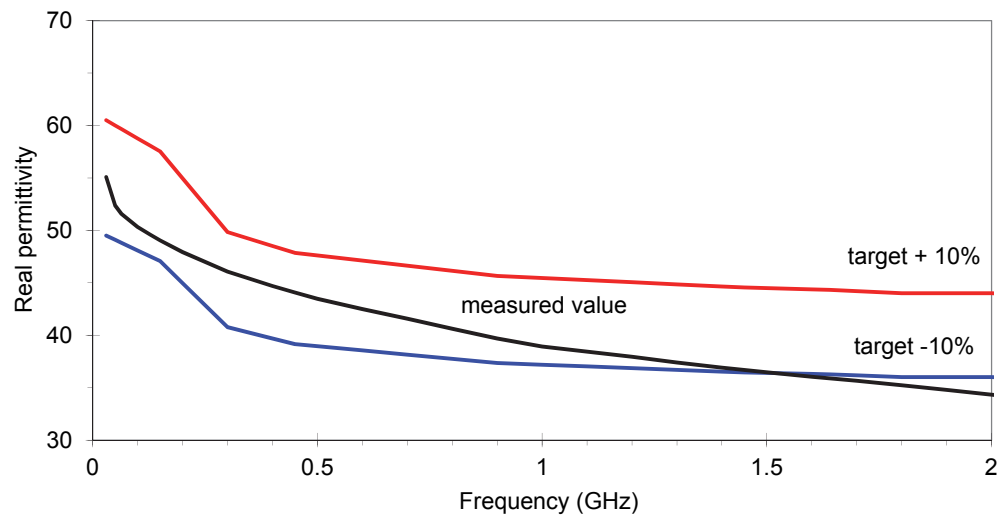


**Figure 25:** Permittivity versus frequency for 150 MHz head phantom permittivity at 22 °C.

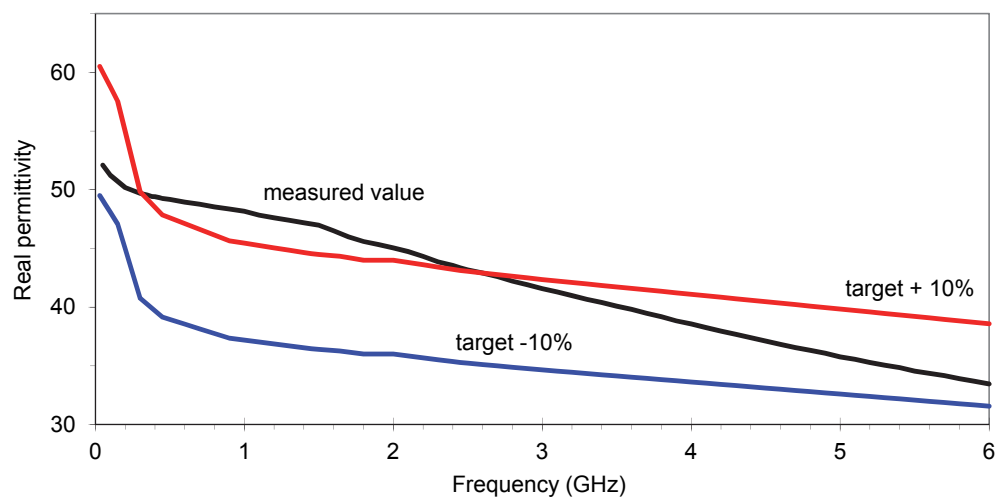


**Figure 26:** Conductivity versus frequency for 5-6 GHz head phantom permittivity at 22 °C.

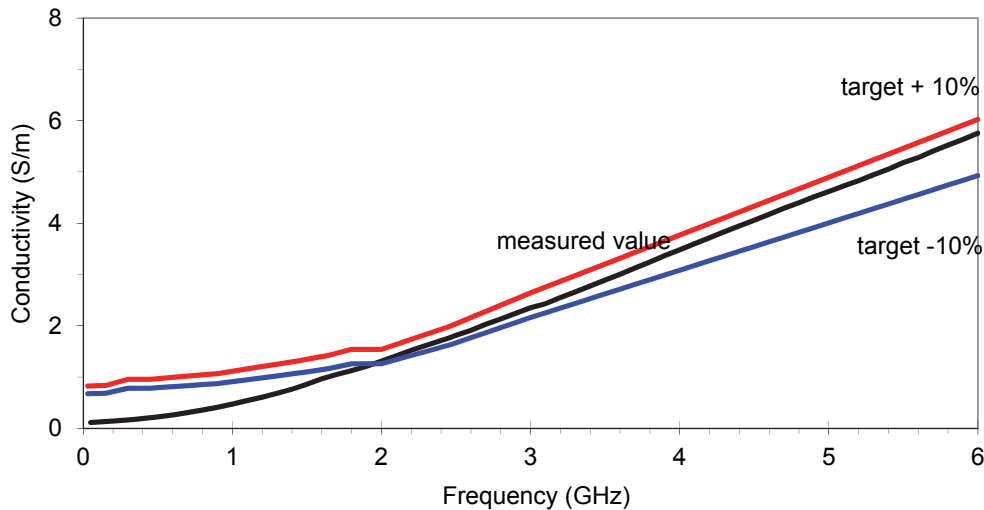


**Figure 27:** Permittivity versus frequency for 5-6 GHz head phantom permittivity at 22 °C.

#### 4.3 STABILITY OF POLYSORBATE-BASED PHANTOMS WITH TIME

The phantom properties may change due to:

- Growth of moulds.
- Evaporation of water.
- Electrolytic reactions (if used in systems with dissimilar metals).
- Prolonged exposure to ultraviolet (UV) light or heating above 38°C can which can cause irreversible changes in the properties of the polysorbate.

The head and body phantoms presented in Table 9 are used at NPL for calibrating SAR probes in waveguide systems, and for SAR measurements. The complex permittivity of the liquids is measured each time they are employed and some histories extend back for 6 years. To investigate the long-term stability of the phantoms, one hundred and sixty measurements have been analysed. Figure 28 shows the percentage of the phantoms which became out of tolerance as a function of age. Twenty five percent of the phantoms went out of specification within one year, mainly due to mould growth. The remaining phantoms have been found to be stable for long periods. At age eighteen months, 70% of the phantoms remained within the  $\pm 5\%$  tolerance, and some remained within this tolerance till age six years. Ninety-five percent of the measured values were within  $\pm 10\%$  tolerance over the six-year period, indicating the benefit of using a 10% tolerance in terms of longevity. Changes in the complex permittivity of the phantoms resulted from growth of moulds and from evaporation of water, which is most pronounced for the 5.8 GHz phantoms.

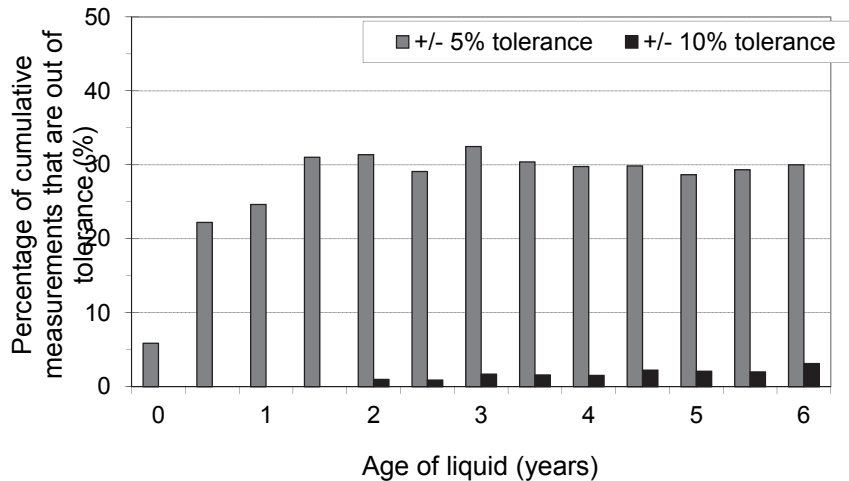


**Figure 28:** Percentage of phantoms that are out of specification as a function of age for a 5% or 10% tolerance. Increasing the tolerance to 10% increases the longevity of phantoms greatly.

## 5 POLYSORBATE-BASED PHANTOMS FOR THE FREQUENCY RANGE 6 GHz TO 10 GHz

Liquid phantoms are required for measuring the SAR from mobile telecommunications devices, and at present these phantoms are only specified for frequencies up to 6 GHz. At present, ICNIRP [1] specifies SAR as the basic restriction up to 10 GHz. Above this frequency power flux density forms the basic restriction. ICNIRP are currently beginning the process of reviewing the RF limits, and it is likely that the upper frequency for SAR may be reduced. The rationale for this is partly the difficulty in measuring SAR above 6 GHz due to the high field gradients that exist within the tissues and phantoms at these frequencies [51], and partly to be in line with the current IEEE exposure standard [43, 52].

This section derives target values for the real part of the permittivity and conductivity of head and body phantoms for the 6 GHz to 10 GHz frequency range, as required for testing some ultra-wide-band systems operating in this frequency range. Finite Difference Time Domain (FDTD) modelling demonstrates that the head phantom liquid provides a conservative estimate of the SAR in the human head. Recipes for non-toxic liquid phantoms based on polysorbates that have the required properties are given.

### 5.1 DERIVATION OF TARGET PROPERTIES FOR HEAD AND BODY PHANTOMS FOR 6 GHz TO 10 GHz

The target values for the real part of the permittivity and conductivity of head and body phantoms specified by the IEEE [43] and FCC [6] respectively were extrapolated to 10 GHz using the frequency response of muscle (for body phantom) and the average brain grey matter and white matter (for head phantom) obtained from [7]. The resulting target values for the frequency range 3 GHz to 10 GHz can be obtained from eqns. 4 to 7, which define a straight line for the real part of the permittivity  $\epsilon'$  versus frequency, and parabola for the conductivity  $\sigma$  versus frequency, as shown in Figure 29.

**Head Phantom Target Values**

$$\varepsilon' = -1.123 \times f + 41.77 \quad (4)$$

$$\sigma = 0.0455 \times f^2 + 0.6702 \times f - 0.1207 \quad (5)$$

[Frequency  $f$  in GHz]

**Body Phantom Target Values**

$$\varepsilon' = 1.337 \times f + 56.19 \quad (6)$$

$$\sigma = 0.0622 \times f^2 + 0.6721 \times f - 0.0409 \quad (7)$$

[Frequency  $f$  in GHz]

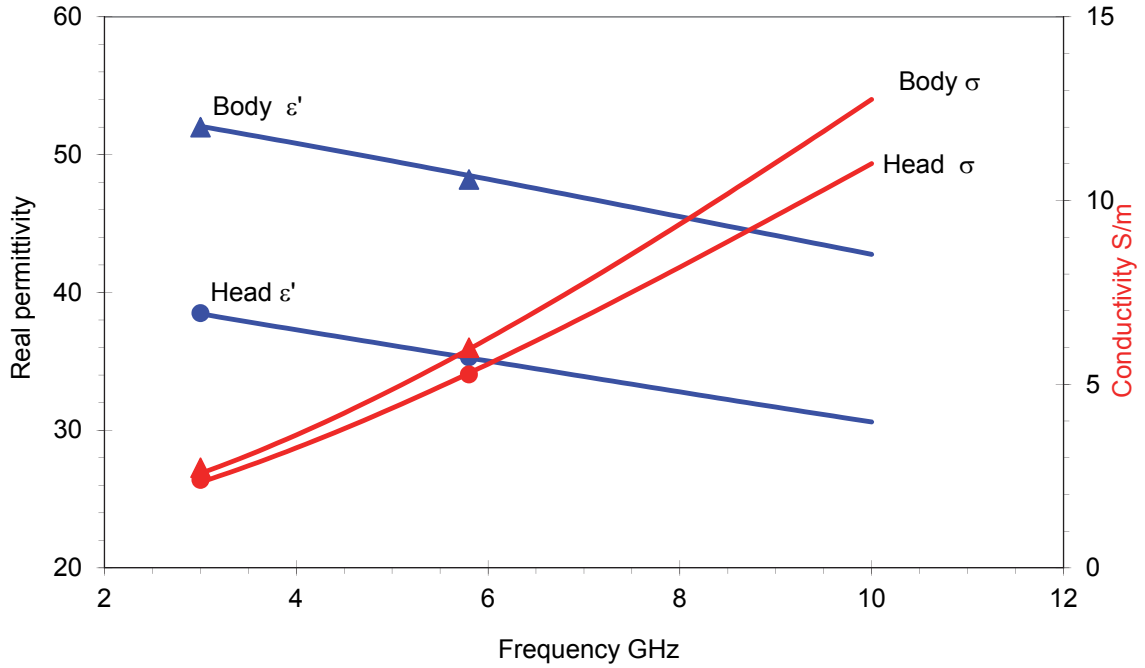


**Figure 29:** Head and body (muscle) phantom target properties for 3 GHz to 10 GHz. The FCC and IEEE target values are shown as triangles and circles respectively.

## 5.2 VERIFICATION THAT THE PHANTOM IS CONSERVATIVE WITH RESPECT TO HEAD SAR

To test whether a homogeneous phantom with these properties is conservative with respect to the human head, the effect of exposure of a portion of head from the human voxel data set, HUGO [51] was simulated using CST Microwave Studio [53], as shown in Figure 30. Calculated 1 g-averaged and 10 g-averaged SAR values were compared to the SAR values for the same geometry, but having uniform dielectric properties, as specified by eqns. 4 and 5, and with a density of  $1.02 \text{ g cm}^{-3}$ .

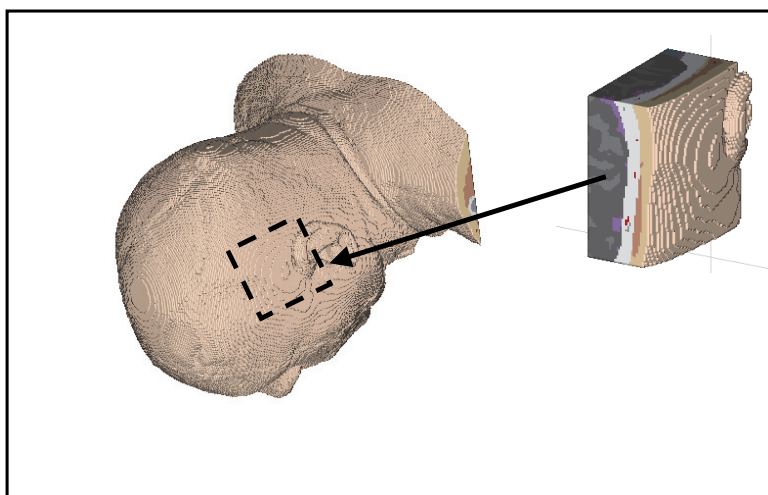


**Figure 30:** HUGO head, showing the region used for the simulations.

Table 10 gives the percentage difference between the SAR in the phantom and the SAR in the head. The 1 g-averaged SARs are higher in the homogeneous phantom compared to the multi-tissue head model in all cases, and the phantom becomes increasingly conservative as the frequency increases for this region. The reason for this is shown in Figure 31, which shows the point SAR as a function of distance into the head. More energy is absorbed in the tissues near the surface of the head at the higher frequencies, and these have lower conductivity than the phantom for this region of the head, which leads to the phantom becoming increasingly conservative.

The cheek region was also modelled, as this region has more fat and muscle which will yield a higher 10 g averaged SAR. In this case the 10 g averaged SAR in the cheek is only 6% higher for the homogeneous phantom at a frequency of 10 GHz. Thus the phantom with the properties defined by eqns 4 and 5 provide a conservative estimate for the head SAR for the regions and frequencies examined, and the degree of over-estimation of head SAR is not excessive.

**Table 10:** Percentage difference between the phantom SAR and head SAR.

| Frequency (GHz) | Region | $\Delta$ 1g SAR Head Phantom (%) | $\Delta$ 10g SAR Head Phantom (%) |
|-----------------|--------|----------------------------------|-----------------------------------|
| 6               | Head   | +7.5%                            | +0.4%                             |
| 8               | Head   | +35.8%                           | +21.2%                            |
| 10              | Head   | +57.2%                           | +53.0%                            |
| 10              | Cheek  | +23.9%                           | +6.23%                            |

Phantoms having these target properties were developed for 6 GHz, 8 GHz and 10 GHz and the recipes are shown in Table 11. The conductivity of the polysorbate 80 mix used at 6 GHz becomes too high above this frequency, so that it was necessary to use polysorbate 85 for the 8 GHz liquid. The measured permittivity and conductivity of the 8 GHz and 10 GHz liquids are

shown in Figures 32 and 33, together with the  $\pm 10\%$  tolerance of the target values, shown as vertical error bars. The 8 GHz phantom was within  $\pm 10\%$  of the target values from 6 GHz to 9 GHz. The conductivity of the 10 GHz phantom is within specification, but the target permittivity could not be obtained. The actual value is low, and this will yield an over-estimate for SAR.

**Table 11:** Mixes for head phantoms in the frequency range 6 GHz to 10 GHz.

| Frequency<br>GHz | Type | Polysorbate<br>20 | Polysorbate<br>80 | Polysorbate<br>85 | De-ionised<br>water | NaCl |
|------------------|------|-------------------|-------------------|-------------------|---------------------|------|
| 6                | Head | 0%                | 37%               | 0%                | 62.7%               | 0%   |
| 8                | Head | 14%               | 0                 | 17.1%             | 67.8%               | 1%   |
| 10               | Head | 0%                | 33%               | 0%                | 66%                 | 0%   |

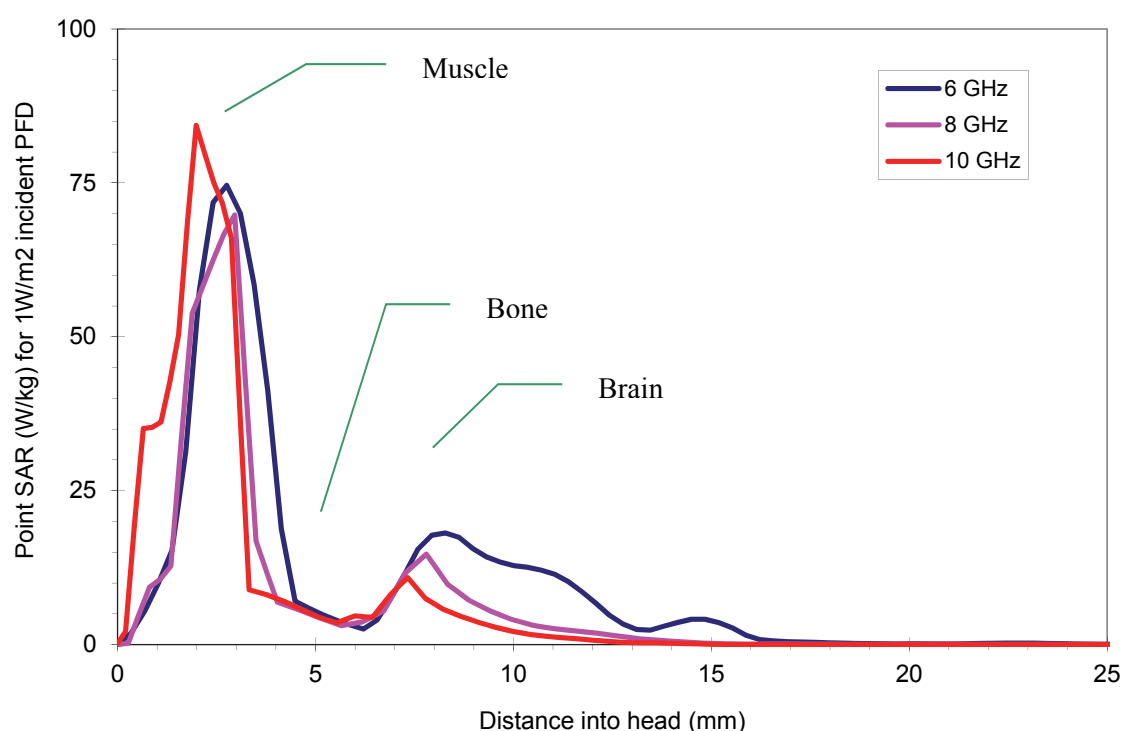


**Figure 31:** The point SAR against distance into the heterogeneous head model at different frequencies. More energy is absorbed in the tissues near the surface of the head as the frequency increases. Because these tissues have lower conductivity than brain the homogeneous phantom becomes increasingly conservative for this region.

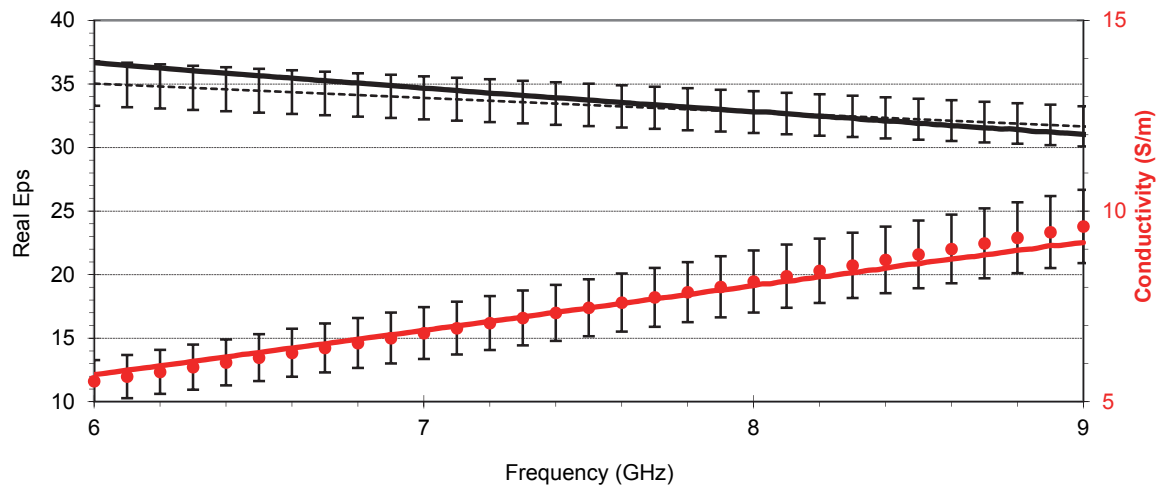


**Figure 32:** Head phantom for 8 GHz, showing the measured conductivity and permittivity at 22 °C. Vertical bars indicate the  $\pm 10\%$  tolerance on the target values. The phantom can be used from 6 GHz to 9 GHz.

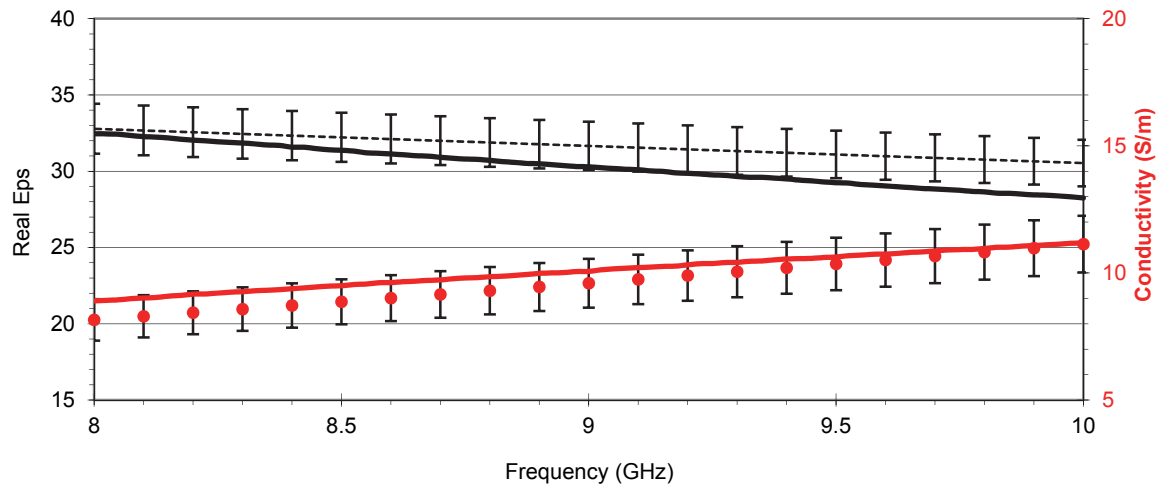


**Figure 33:** Head phantom for 10 GHz, showing the measured conductivity and permittivity at 22 °C. Vertical bars indicate the  $\pm 10\%$  tolerance on the target values. The real part of the permittivity cannot be achieved at 10 GHz with these mixes.

## 6 PHANTOMS FOR MEASUREMENT OF INDUCED HEATING ASSOCIATED WITH MEDICAL IMPLANTS AT 64 MHz AND 128 MHz MRI FREQUENCIES

Characterisation of passive medical implants such as stents to determine associated temperature rises during Magnetic Resonance Imaging (MRI) is required for the safety of patients. The required frequencies are typically 64 MHz and 128 MHz (according to the type of MRI machine). The procedure specified by the ASTM standard [30] requires measurements of the temperature increase caused by RF exposure for a known interval on two phantoms that have the same specified conductivity:

- A low viscosity phantom (which is stirred after exposure to determine the average temperature rise from which Whole-Body SAR is calculated).
- A viscous gel phantom from which local temperature rises in proximity to implants placed in the phantom is determined. The purpose of using a gel phantom is to reduce thermal convection.

For both phantoms conductivity  $0.47 \text{ S/m} \pm 10\%$  at both frequencies is specified. There is, however, no requirement to measure the permittivity. The standard [30] specifies the mix of ingredients required for making these phantoms: The low viscosity phantom is saline and the viscous phantom is saline and polyacrylic acid partial sodium salt. A short shelf-life (two months) is specified to avoid the need to monitor the phantoms<sup>3</sup>. Measurements of the permittivity and conductivity on samples of the two phantoms prepared at NPL are shown in Tables 5 and 6.

The temperature coefficients of these phantoms are significant, so temperature must be monitored. The conductivity increases by approximately 2.5 % per °C for both phantoms at 64 MHz and 128 MHz. The concentration of salt can be chosen according to the required temperature<sup>4</sup>.

Thermal measurement also requires the specific heat capacity of the phantoms to be known. The value ( $4.16 \text{ Jg}^{-1}\text{K}^{-1}$ ) is cited in reference [30].

## 7 PHANTOMS FOR ASSESSING ANKLE CURRENTS AND WHOLE BODY SAR OVER THE FREQUENCY RANGE 1 MHz TO 30 MHz

ICNIRP [1] specify limits to induced current on account of burn and shock hazards. These apply at frequencies up to 110 MHz (although in this section we will consider phantoms for only the 1 MHz to 30 MHz range). At frequencies in the range 100 kHz to 10 GHz a maximum SAR is also specified. Measurements on industrial sites typically measure the limb currents when a person is exposed to EMF by using a *limb current meter* [54] (which is in essence a transformer clamp and a current meter). In the worst-case exposure scenario, the person acts as a monopole antenna with resonant absorption at  $\sim\lambda/4$  (free-space wavelength) which corresponds to a frequency of 35 MHz for a height of 1.76 m. At resonance, the maximum current flow in an exposed person standing up occurs in the ankles. The resonant frequency depends on the free-space wavelength of the incident field and it is largely independent of the real permittivity of the person. Laboratory-based measurements of ankle current can be made using a limb current meter placed around a phantom shell [55] that contains a liquid or gel phantom that matches the

<sup>3</sup> A measurement is required [30] when the phantom is made to show that the specified conductivity has been obtained.

<sup>4</sup> Reference [30] specifies 2.5g/l concentration for the low viscosity phantom for use at 25 °C. Table 3 gives data for a 2.7g/l phantom suitable for 20 °C to 22 °C.

specified target conductivity. In the simplest design this could be plastic tube 1.76 m length (50% percentile male height) filled by a phantom liquid or gel that is in direct contact with the ground plane. The currents induced when the phantom is exposed to a vertically polarised electric field are measured.

A laboratory-based system for assessment of whole-body exposure uses a homogeneous phantom for which permittivity and conductivity is representative of the volumetric average for the body. Assessment of exposure from body-worn devices requires measurement of local induced currents and SAR. These must account for local variations in the conductivity of tissue, so it may for example be necessary to use a muscle phantom that has a higher conductivity<sup>5</sup> than the whole body average.

The target permittivity values in the 1 MHz to 30 MHz frequency range are lower than that of tissue (see Section 3). Simulations show that in this frequency band the conductivity is much more important than the permittivity. Fortunately, the target values of conductivity can be attained by e.g. adjusting the salt concentration.

In this section, simulations are used to obtain target data for a homogenous phantom suitable for the measurement of ankle current and whole-body SAR, as this is not currently available in standards. The simulations compare homogeneous phantoms of varying conductivity against a heterogeneous phantom that utilises permittivity and conductivity data for different regions of the body. A target permittivity and conductivity that gives conservative measurements of ankle current and whole-body SAR is selected, and a suitable recipe is proposed.

## 7.1 DERIVATION OF TARGET PROPERTIES FOR THE FREQUENCY RANGE 1 MHz TO 30 MHz

Simulations of the above exposure scenario were performed using the time domain solver of CST Microwave Studio [53] and the anatomic model HUGO, derived from the visible man project [56]. HUGO was based on a 38 year old male with height 1.8 m and mass 90.3 kg, with 31 tissue types defined. Tissue properties from Gabriel [7] were used. The simulations were then repeated with the same geometry and meshing but for a homogenous human model with fixed permittivity of 100 (which can be readily realised with gel-based mixes) and conductivity between 0.2 S/m to 0.6 S/m. Figure 34 shows the 10g SAR distribution in the heterogeneous man at 15 MHz, and shows that the highest SAR occur in the ankle regions at this frequency. Figures 35 and 36 show the whole body SAR (WBSAR) and ankle current respectively for different phantom conductivities. The results from the heterogeneous man are also shown. Good agreement between the two models is obtained with permittivity 100 and conductivity 0.3 S/m. By using the homogenous phantom, however, it was not possible to obtain agreement for 10g SAR as well (this was underestimated by a factor of 2 to 3) as the currents in the cross-section of the ankle were very different for the heterogeneous and homogeneous models.

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<sup>5</sup> The conductivity of muscle is 0.50 S/m at 1 MHz and 0.66 S/m at 30 MHz

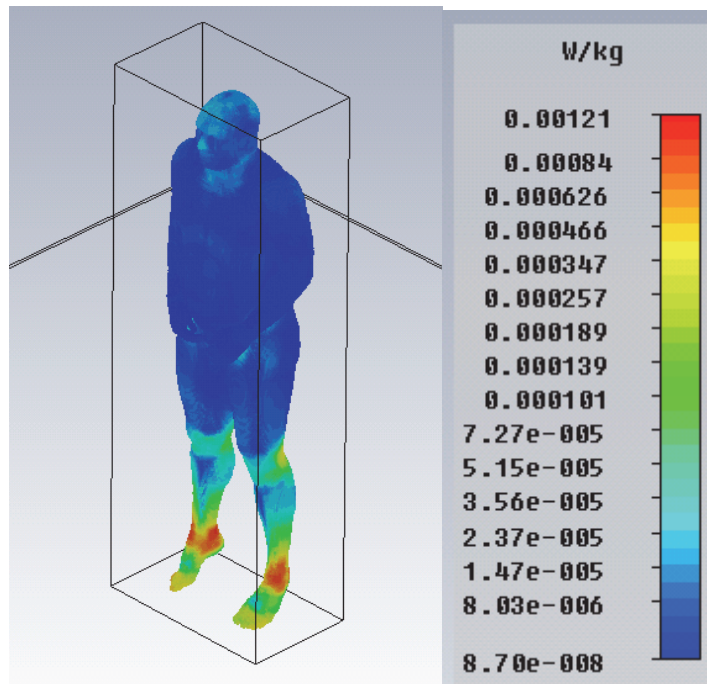


**Figure 34:** 10g-averaged SAR distribution for Hugo model (heterogeneous) standing on a conducting ground plane and exposed to a 15 MHz, 1 Vm<sup>-1</sup> *peak* vertical polarised field. The maximum SAR occurs in the ankles. Very similar SAR distributions are observed for frequencies between 1 and 30 MHz.

## 7.2 RECIPE AND MIXING INSTRUCTIONS

A saline based phantom with salt concentration adjusted to give the target conductivity  $\sigma = 0.3 \text{ Sm}^{-1}$  could be used to fill a phantom shell (e.g. a tube) for measurement of limb current using a limb current meter. The permittivity of saline ( $\approx 80$  in the require frequency range) is lower than the target value (100), but this will not have a large effect on the current readings.

A recipe for a high-viscosity phantom suitable for thermal measurement of SAR as well as limb current is proposed here. The gel phantom recipe specified in the ASTM standard [30] was modified to achieve the target properties of  $\epsilon' = 100$ ,  $\sigma = 0.3 \text{ Sm}^{-1}$  as closely as possible over the frequency range 1 MHz to 30 MHz. Deionised water with added 0.2 g/l NaCl and 10 g/l polyacrylic acid partial sodium salt (PAA-Na) closely matches the required properties at 22°C. The mix is made by first adding 0.2 g/l NaCl to the deionised water and stirring it to dissolve completely. Then add the 10 g/l PAA-Na and stir to suspend completely and leave for 1 hour before blending the mix to a slurry using a kitchen food blender. Repeat the blending process periodically until all lumps are dissolved. Allow to stand for 24 hours then stir well before use.

The real permittivity and conductivity of the phantom were measured using the 44 mm coaxial sensor (50 MHz to 350 MHz) and extrapolated to the 1 MHz to 30 MHz range on the basis of eqn. (3) (power-law) and eqn. (2b). The reasons for using an extrapolation are to improve accuracy (below 30 MHz uncertainties for the 44-mm sensor become large) and to reduce the effects of electrode polarisation – see Section 2.4. The extrapolated results are given in Table 12. The temperature dependences of permittivity and conductivity are seen to be low at 22 °C. The specific heat of the phantom is  $3.97 \text{ J g}^{-1} \text{ K}^{-1}$  at 22 °C, with temperature coefficient of  $+0.0013 \text{ J g}^{-1} \text{ K}^{-1} \text{ per } ^\circ\text{C}$  and the density is very close to  $1 \text{ g cm}^{-3}$ .

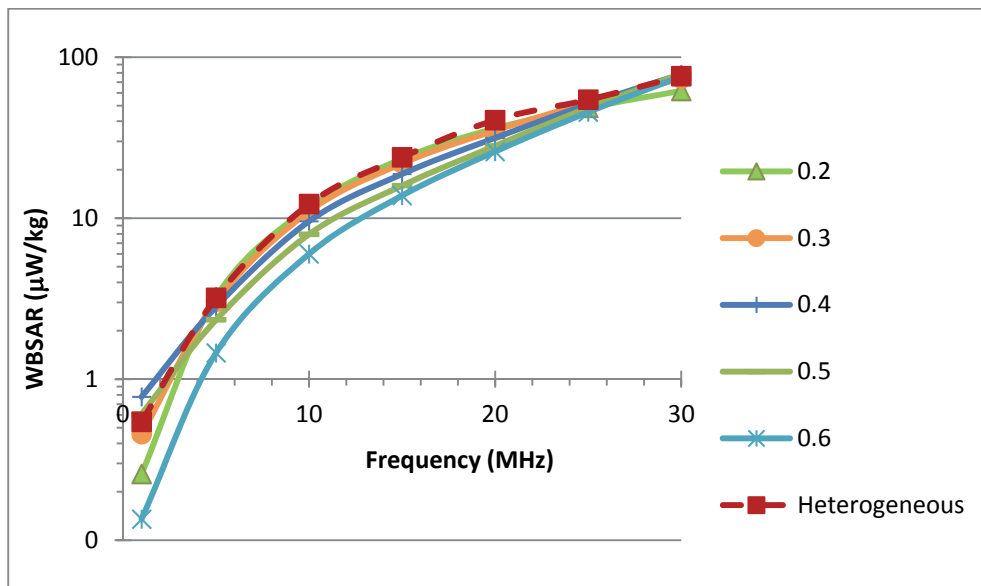


**Figure 35:** WBSAR for homogeneous phantom exposed to  $1 \text{ Vm}^{-1}$  incident field for different phantom conductivities and with  $\epsilon' = 100$  and  $\rho = 1000 \text{ kgm}^{-3}$ . Also shown are the results from the anatomical (heterogeneous) model. Good agreement is obtained at  $\sigma = 0.3 \text{ Sm}^{-1}$ .

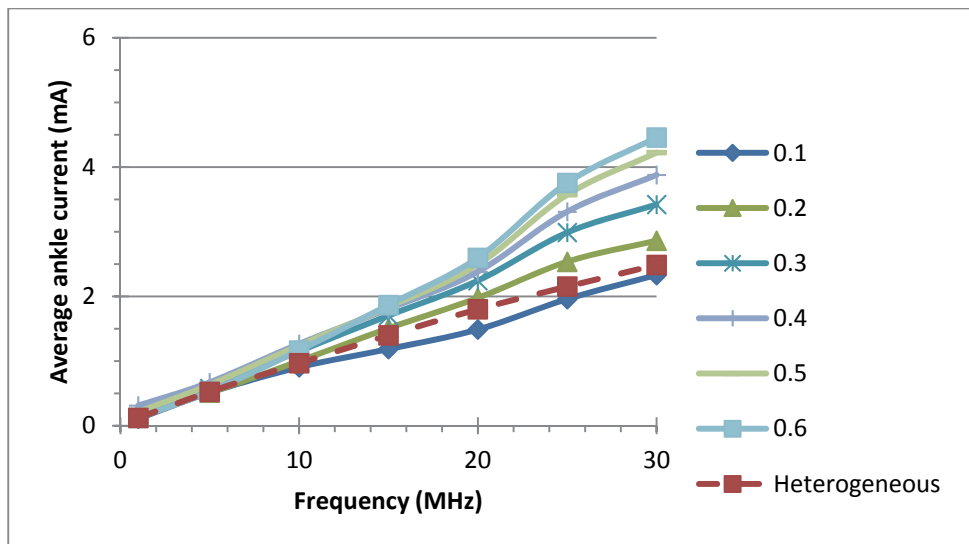


**Figure 36:** Ankle current (average of left and right side) for homogeneous phantom exposed to  $1 \text{ Vm}^{-1}$  incident field for different phantom conductivities ( $\epsilon' = 100$  and  $\rho = 1000 \text{ kgm}^{-3}$ ). Also shown are the results from the anatomical (heterogeneous) model. At  $\sigma = 0.3 \text{ Sm}^{-1}$ , the homogeneous phantom gives an over-estimate of the ankle current.

### 7.3 VERIFICATION THAT THE PHANTOM IS CONSERVATIVE WITH RESPECT TO ANKLE CURRENT AND WHOLE BODY SAR

Simulations for a homogeneous man were also performed using the extrapolated permittivity and conductivity data of the phantom at 22°C that are shown in Table 12. Table 13 gives the ratio of the phantom results to human model results for SAR averaged over the whole phantom, ankle current, and local SAR averaged over a 10g cube. The phantom provides a close approximation for whole body SAR, a conservative estimate for the ankle current, but the 10g SAR is lower by a factor of 2 to 3 times. Whilst the total ankle currents are comparable, the current flows preferentially in the tendons and muscle of the human model due to the presence of the low conductivity bone, which accounts for this difference.

**Table 12:** Permittivity and conductivity of the homogeneous 1 MHz to 30 MHz phantom. The measurements were made with a 44-mm coaxial sensor with cylindrical cavity (Figure 8) and extrapolated to the specified frequency range. Data at four temperatures is shown.

| Frequency (MHz) | Sample temperature |                |             |                |             |                |             |                |
|-----------------|--------------------|----------------|-------------|----------------|-------------|----------------|-------------|----------------|
|                 | 12.8 °C            |                | 22 °C       |                | 23.8 °C     |                | 35 °C       |                |
|                 | $\epsilon'$        | $\sigma$ (S/m) | $\epsilon'$ | $\sigma$ (S/m) | $\epsilon'$ | $\sigma$ (S/m) | $\epsilon'$ | $\sigma$ (S/m) |
| 1               | 115                | 0.318          | 114         | 0.311          | 113         | 0.337          | 106         | 0.472          |
| 5               | 106                | 0.318          | 104         | 0.311          | 103         | 0.337          | 97          | 0.472          |
| 10              | 102                | 0.318          | 100         | 0.311          | 100         | 0.337          | 93          | 0.472          |
| 15              | 100                | 0.319          | 98          | 0.312          | 97          | 0.338          | 91          | 0.472          |
| 20              | 99                 | 0.319          | 96          | 0.312          | 96          | 0.338          | 89          | 0.473          |
| 25              | 98                 | 0.319          | 95          | 0.312          | 95          | 0.338          | 88          | 0.473          |
| 30              | 97                 | 0.320          | 94          | 0.312          | 94          | 0.338          | 87          | 0.473          |

**Table 13:** Comparison of results of whole body SAR, 10g-SAR and ankle current for homogeneous and heterogeneous human models based on the HUGO visible human data set. The homogeneous model has all tissue types set to the measured values for the 1 MHz to 30 MHz phantom at 22 °C and with  $\rho = 1003 \text{ kg m}^{-3}$ .

| Frequency (MHz) | Ratio of whole body SAR (phantom/person) | Ratio of ankle current (phantom/person) | Ratio of 10g average SAR (phantom/person) |
|-----------------|------------------------------------------|-----------------------------------------|-------------------------------------------|
| 1               | 0.84                                     | 1.04                                    | 0.49                                      |
| 5               | 0.96                                     | 1.11                                    | 0.35                                      |
| 10              | 0.89                                     | 1.21                                    | 0.35                                      |
| 15              | 0.90                                     | 1.23                                    | 0.34                                      |
| 20              | 0.90                                     | 1.30                                    | 0.27                                      |
| 25              | 1.01                                     | 1.37                                    | 0.39                                      |
| 30              | 1.04                                     | 1.45                                    | 0.31                                      |
| average         | <b>0.95</b>                              | <b>1.34</b>                             | <b>0.36</b>                               |

## 8 CONCLUSIONS

VNA-based methods of measuring the dielectric permittivity and conductivity of phantom materials in the frequency range 30 MHz to 10 GHz using electroded sensors and cells have been reviewed. The availability of data for reference liquids required for calibration and for checking measurements has been discussed (this is a particular issue for the frequency range 5 GHz to 10 GHz as there are fewer sources of data).

Coaxial reflection cells and large-sized coaxial sensors were used to make measurements of the dielectric permittivity and conductivity of phantoms at frequencies in the range 10 MHz to 350 MHz on phantoms. As the frequency is reduced below 30 MHz a substantial increase in the *apparent* permittivity is observed on account of Electrode Polarisation (EP). At frequencies in the range 30 MHz to 50 MHz the effect of EP is small, and above that it is not evident at all. While EP is widely reported and understood for instrumentation such as admittance cells that work in the kHz – MHz range, the majority of papers on RF methods such as coaxial sensors report do not report measurements at as low as 30 MHz (as typically small-sized sensors that do not have the required sensitivity are used). Some researchers therefore may not appreciate that measurements on liquid phantoms made using electroded instruments that do work at these lower frequencies are likely to be subject to significant EP effects. Inevitably, this also applies to the biomaterials which phantoms have been designed to simulate. The presence of biological structures such as cells is reported to cause a shielding effect [57] which is expected to cause the frequency range at which EP occurs to be shifted downwards. Measurements with four-point probes [25] are much less prone to the effects of EP. The maximum useful frequency for four point probes, however, appears to be approximately 1 MHz as at higher frequencies measurements are affected by inductance of connections and electrodes.

Methods for extrapolating measurements made in the frequency range 50 MHz to 350 MHz to 30 MHz and lower (where EP can be a serious issue for permittivity measurement) have been applied successfully for salt solutions and polysorbate-based phantoms. Extrapolation techniques, however, are found not to have sufficient accuracy for a phantom that contains a polymer gelling agent as the presence of macromolecules causes dispersions that have significant effect.

Inductive conductivity meters allow static conductivity to be measured without error caused by EP. They can be used for monitoring changes in the properties of some types of phantom instead of RF techniques to reduce cost. The RF and static conductivity diverge as the frequency is increased (see Figure 3) and so, depending on the recipe and frequency, the RF conductivity may be significantly higher than the static conductivity (and may exceed the permitted 10% tolerance that standards typically specify for the conductivity of phantoms). A commercially-available inductive probe was used to measure the static conductivity of three phantoms (see Table 5–7). It was observed that measurements by this technique are more repeatable for low-viscosity samples such as salt solutions. The measurements were compared to measurements of RF conductivity made by using coaxial sensors and cells. For saline (2.7g/l) the RF and static conductivity differ negligibly at frequencies up to 128 MHz (and are within 5% at 300 MHz). The static conductivity of polysorbate and gel-based recipes is significantly lower than that at MHz frequencies, but if this is understood inductive conductivity meters may nevertheless be useful for monitoring phantoms at the lower end of the spectrum (e.g. up to 150 MHz).

Non-toxic recipes for head and body phantoms based on polysorbate 20 or polysorbate 80 mixed with water and salt are presented for frequencies between 30 MHz and 6 GHz. Measurements show the complex permittivity of these liquids is stable for periods up to six years, and that the temperature coefficient is low (<5 % per °C). The effect of recent changes in IEEE and IEC standards [4-5, 43] to relax the tolerance for the real part of the permittivity and conductivity

from  $\pm 5\%$  to  $\pm 10\%$  is to approximately double the frequency bandwidth for which the liquid properties are in specification, and to increase the useful life of the phantoms, with economic advantages to laboratories performing Specific Absorption Rate (SAR) measurements.

Recipes for head and body phantoms for 6 GHz, 8 GHz and 10 GHz have also been formulated on the basis of target values extrapolated from data for brain and muscle given at lower frequencies in the existing standards (as target values for these frequencies are not given currently). The 8 GHz mix, which is based on polysorbate 85, can be used over the frequency range 6 to 9 GHz as both the conductivity and permittivity are within a 10% tolerance. The 10 GHz mix met the target value of conductivity, but the real part of the permittivity was too low. In practice, this will cause measured SAR to be increased above its true value, so the assessment of SAR will be conservative.

Extrapolating the existing phantom properties according to the frequency response of brain and muscle provides target permittivity and conductivity for head and body phantoms in the frequency range 6 GHz to 10 GHz which are conservative with respect to the SAR in the human head or body. In the case of the head, computer simulations show that the head phantom is conservative for both 1g and 10g averaged SARs. For the region of the head above the ear, the phantom becomes increasingly conservative, and at 10 GHz over-estimates the 1g and 10g volume averaged head SAR by more than 50%. This is because at the higher frequencies a higher proportion of the incident energy is absorbed in the surface tissues, which have lower conductivity than the brain. However, for the cheek region the volume averaged SARs in the head are higher, due to the higher volume of muscle and fat in this region, and the phantom over-estimates the 10g SAR by only 6% at 10 GHz.

Heterogeneous and homogeneous whole-body phantoms were compared using simulations to derive target permittivity and conductivity values for homogeneous phantoms for the frequency range 1 MHz to 30 MHz. A recipe for a phantom gel that is suitable for induced current measurements (e.g. ankle) and thermal measurement of SAR in this frequency range has been proposed.

## 9 ACKNOWLEDGEMENT

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## APPENDIX: CHEMICAL SUPPLIERS

Polysorbate 20 (trade name Tween 20), polysorbate 80 (trade name Tween 80) and polysorbate 85 (trade name Tween 85).

NBS Biologicals Ltd  
14 Tower Square  
Huntingdon  
Cambs  
PE29 7DT  
England  
[mark@nbsbio.co.uk](mailto:mark@nbsbio.co.uk) or [info@nbsbio.co.uk](mailto:info@nbsbio.co.uk)  
[www.nbsbio.co.uk](http://www.nbsbio.co.uk)

Sigma-Aldrich Ltd  
The Old Brickyard  
New Road  
Gillingham  
Dorset  
SP8 4XT  
  
[ukorders@sial.com](mailto:ukorders@sial.com)  
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