Published in final edited form as:

Meas Sci Technol. 2009 February 19; 20(4): . doi:10.1088/0957-0233/20/4/045702.

Precise dielectric property measurements and E-field probe calibration for specific absorption rate measurements using a rectangular waveguide

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Abstract

Specific absorption rate (SAR) measurements require accurate calculations of the dielectric properties of tissue-equivalent liquids and associated calibration of E-field probes. We developed a precise tissue-equivalent dielectric measurement and E-field probe calibration system. The system consists of a rectangular waveguide, electric field probe, and data control and acquisition system. Dielectric properties are calculated using the field attenuation factor inside the tissue-equivalent liquid and power reflectance inside the waveguide at the air/dielectric-slab interface. Calibration factors were calculated using isotropicity measurements of the E-field probe. The frequencies used are 900 MHz and 1800 MHz. The uncertainties of the measured values are within $\pm 3\%$, at the 95% confidence level. Using the same waveguide for dielectric measurements as well as calibrating E-field probes used in SAR assessments eliminates a source of uncertainty. Moreover, we clearly identified the system parameters that affect the overall uncertainty of the measurement system.

Keywords

dielectric property measurement; SAR; dosimetry; E-field probe; E-field probe calibration; waveguide; uncertainty analysis

1. Introduction

At the frequencies of operation of most mobile phones, concerns about the exposure to radiofrequency (RF) radiation center on induced tissue heating from the exposure. The heating is related to the specific absorption rate (SAR) and other thermodynamic properties of the body tissues that are exposed to RF. Guidance, or reference levels, of exposure are provided for device compliance testing [1, 2]. Compliance tests [3, 4] require precise measurements of dielectric properties of tissue-equivalent liquids [5–8] and associated E-

field probe calibration [9–11] used for SAR measurements in phantoms simulating the human body.

RF dosimetry is the process that quantifies the magnitude and distribution of the RF energy absorbed by an object when it is exposed to RF fields. A principal parameter measured in RF dosimetry is the SAR. In the safety context, the SAR is the rate at which RF energy is absorbed in human tissues due to the exposure to RF radiation. The SAR is expressed in W kg^{-1} . The SAR value is related not only to the incident electromagnetic (EM) waves but also to the electrical and geometrical characteristics of the exposed tissue. The SAR is strongly related to the incident electric field strength E as well as to the dielectric properties of the tissue, (1):

$$\text{SAR} = \frac{\sigma}{2\rho} |E|^2 = c \frac{\partial T}{\partial t}, \quad (1)$$

where σ is the tissue conductivity (S m^{-1}), ρ is the density of the averaging mass which is any 1 g or 10 g of contiguous tissue (kg m^{-3}), $|E|$ is the magnitude (V m^{-1}) of the local electric field vector (2), $\frac{\partial T}{\partial t}$ is the rate of temperature rise (K s^{-1}) and c is the tissue-specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$).

We developed a precise measurement system which calculates the real and imaginary parts of the complex permittivity and the E-field probe calibration factors of all three orthogonal dipoles simultaneously. The system consists of a rectangular waveguide, electric field probe, and data control and acquisition system. The use of waveguides has some clear advantages: no anechoic chamber shielding is needed to minimize multipath reflections of the calibration field or shield-radiated interference, the system is compact and the RF power needed is minimized. Using the same waveguide for dielectric measurements as well as calibrating E-field probes used in SAR assessments eliminates a source of uncertainty. Moreover, we clearly identified the system parameters that affect the overall uncertainty of the measurement system.

2. Materials and methods

The measurement system consists of a rectangular waveguide, E-field probe, and a data acquisition system and control (figure 1). These components are described below. The real and imaginary parts of the dielectric properties are calculated using the field attenuation factor inside the tissue-equivalent liquid and power reflectance inside the waveguide at the air/dielectric-slab interface. The calibration factors for each orthogonal dipole are simultaneously calculated using isotropicity measurements where the probe is rotated about its axis in incremental steps of 60° .

2.1. Waveguide

The central component is a vertically mounted rectangular waveguide (figure 1). The upper part of the waveguide is separated from the lower part by a watertight dielectric slab (acrylic). The upper part of the waveguide is filled with a tissue-equivalent liquid. The depth

of the liquid should be at least thrice the skin depth of the liquid (where the E-field falls to $1/e$) to ensure decay of the fields in the liquid, thereby preventing reflections from the liquid/air surface. The width of the dielectric slab ($\sim \lambda/4$) is set to minimize reflections at the air/dielectric-slab interface, hence maximizing the power absorbed in the tissue-equivalent liquid. The waveguides used are described in table 1.

2.2. E-field probe

To measure the electric field inside the tissue-equivalent liquid, a miniature electric field probe, consisting of three orthogonal dipole sensors, is used (SPEAG ET3DV6R) (figure 2). The probe tip must be much smaller than the wavelength in the tissue-equivalent liquid, isotropic (since the orientation of the measured field is generally unknown), exhibit a linear response to the square of the incident electric field strength and should be transparent (non-perturbing) to the measured field [12–15]. In the square-law region where the measured voltage is proportional to the input power, $|E_i|^2 = V_i/k_i$, the measured electric field is calculated using (2). The square-law behavior is demonstrated by varying the input power to the waveguide and observing the output of the probe. By varying the input power from 10 to 25 dBm, the probe's DC voltage increased linearly proportional to the input power within $\pm 1\%$.

$$|E| = \sqrt{|E_1|^2 + |E_2|^2 + |E_3|^2} = \sqrt{\frac{V_1}{k_1} + \frac{V_2}{k_2} + \frac{V_3}{k_3}}, \quad (2)$$

where E_i , V_i and k_i are the corresponding electric field strength, voltage (V) and calibration factor ($\text{mV (V m}^{-1})^{-2}$) of dipole i ($i = 1, 2, 3$).

2.3. Tissue-equivalent liquid

Tissue-equivalent liquids are used to simulate human tissues in phantoms for SAR measurements and as part of the process of calibrating E-field probes. The dielectric parameters required are the complex relative permittivity of the tissue-equivalent liquid at specific test frequencies, (3):

$$\epsilon_r = \epsilon' - j\epsilon'' \quad (3)$$

$$\sigma = \omega \epsilon_0 \epsilon'', \quad (4)$$

where ϵ_r is the liquid relative permittivity, ϵ' and ϵ'' are the real and imaginary parts of the complex permittivity, respectively, ϵ_0 is the free space permittivity (F m^{-1}), ω is the angular frequency (s^{-1}) and j is the imaginary unit equal to the square root of -1 , $\sqrt{-1}$.

Since the dielectric properties are frequency dependent, a different liquid must be formulated for each test frequency band. Standards provide specific requirements for the

permittivity and conductivity at each frequency band (table 2) [4] and suggest recipes for suitable tissue-equivalent liquids.

However, following the recipes does not always produce the correct value, partly because of inaccuracies in mixing and partly because of variations in the properties of each ingredient. Because the accuracy of SAR measurements depends on the dielectric properties of the tissue-equivalent liquid, it is not sufficient to use the dielectric values specified in the standards [16–19]; actual values must be precisely measured and used in the computation of SAR.

2.4. Data acquisition and control

To generate the RF test signal, a signal generator (Hewlett Packard HP8657B) and an RF power amplifier (Mini-Circuits ZHL-42) are used. The signal generator is controlled via IEEE 4888 bus so that the waveform, shape, frequency and amplitude of the signal produced can be specified using a computer. A directional coupler is connected to the output of the RF power amplifier so that the forward and reflected powers from the amplifier to the waveguide containing the dielectric materials can be measured with a power meter (Giga-Tronics 8542C).

Custom software is written in LABVIEW 5.1 to control the delivery of RF energy, position the probe inside the waveguide and collect the probe's output and power readings. The DC voltage from each orthogonal dipole is amplified using a custom-built low-noise DC amplifier. MATLAB is used for post-processing.

The probe position is controlled by a three-axis scanner. Precision step motors move the probe in the x , y (Astrosyn 23KM-K711-02 No. T7410) and z (Astrosyn 23LM-C304-58 No. T7710) directions. The step size for the stepper motors is $1.8^\circ \pm 5\%$. The scanning system has a resolution of 98.2 steps per millimeter or a minimum step size of $10.18 \mu\text{m}$ per step.

2.5. Dielectric property measurement

The real and imaginary permittivities of the tissue-equivalent liquid are calculated using the field attenuation factor inside the tissue-equivalent liquid and power reflectance at the air/dielectric-slab interface [20]; this procedure is discussed below.

E-field probes must be calibrated for different tissue-equivalent liquids they are used in; this is enabled using the calibration factors k_i as indicated in (2). Therefore, it is difficult to measure the dielectric properties of a tissue-equivalent liquid without prior knowledge of the associated calibration factors for each orthogonal dipole. However, since the calibration factors only affect the magnitude of the measured field and not the attenuation factor, and for the purpose of measuring the tissue-equivalent dielectric properties, the calibration factors can be consolidated into one calibration factor without loss of generality. The measured electric field can be written as in (5):

$$|E| = \sqrt{\frac{1}{K}(V_1 + V_2 + V_3)} = \sqrt{\frac{1}{K}(V_t)}, \quad (5)$$

where V_t is the total measured voltage and K is the consolidated calibration factor.

A tissue-equivalent liquid temperature increase is negligible for the duration of the experiment which is around 1 min at a single power level. From equation (1), the temperature rise time, for 1 W of absorbed power near the dielectric-slab/liquid interface, is about $0.001 \text{ } ^\circ\text{C s}^{-1}$ for both 900 MHz and 1800 MHz.

2.5.1. Attenuation factor—A scan along the waveguide z -axis is performed with the E-field probe, and the probe voltage is then measured as a function of net power and position in the liquid (figure 3(a)). The probe must be at the same angular position about its axis during the scan along the z -axis. The probe tip should not be close to the dielectric-slab/liquid interface (less than one probe-tip diameter), to avoid field distortion due to coupling effects (boundary effect) [13, 21], or too far from the dielectric-slab/liquid interface, where the field has decayed significantly (skin depth).

From the theoretical formula for the fundamental mode, TE_{10} , inside the waveguide, the electric field inside the tissue-equivalent liquid is given by (6). The attenuation factor α , (7), is calculated by using an exponential curve fit:

$$\frac{V_t}{P_{\text{net}}} = A e^{-z\alpha} \quad (6)$$

$$\alpha = \frac{\omega^2 \mu_0 \varepsilon_0 \varepsilon''}{\beta} \quad (7)$$

$$A = K \frac{4\omega\mu_0}{ab2\beta} \sin\left(\frac{\pi}{a}(x \pm x_0)\right) e^{\mp z_0\alpha} \quad (8)$$

$$\beta = \sqrt{\omega^2 \mu_0 \varepsilon_0 \varepsilon' - \left(\frac{\pi}{a}\right)^2}, \quad (9)$$

where P_{net} is the net dissipated power (W) in the tissue-equivalent liquid, A is a constant, x_0 is the uncertainty in the E-field probe location along the x -axis ($x \pm x_0$), a and b are the cross-sectional dimensions of the waveguide, z_0 is the uncertainty in the E-field probe

location along the z -axis ($z \pm z_0$), μ_0 is the free space permeability (H m^{-1}), β is the propagation constant and e is Euler's number or Napier's constant.

Since the fitting parameters are A and α , and the uncertainties associated with the probe position, x_0 and z_0 , are included in the magnitude A , the desired parameter α is independent of positioning errors.

2.5.2. Power reflectance—The power reflectance at the air/dielectric-slab interface is calculated using the measured forward and reverse powers (figure 4(a)).

The analytical formula for the power reflectance as a function of ϵ' and ϵ'' at the air/dielectric-slab interface is given by (10) [20]:

$$|\Gamma_1|^2 = \left| \frac{\rho_1 + \rho_2 e^{-2j\beta_r d_r} + \rho_1 \rho_2 \rho_3 e^{-2j\beta_s d_s} + \rho_3 e^{-2j\beta_r d_r} e^{-2j\beta_s d_s}}{1 + \rho_1 \rho_2 e^{-2j\beta_r d_r} + \rho_2 \rho_3 e^{-2j\beta_s d_s} + \rho_1 \rho_3 e^{-2j\beta_r d_r} e^{-2j\beta_s d_s}} \right|^2, \quad (10)$$

where

$$\rho_1 = \frac{Z_r - Z_0}{Z_r + Z_0}, \quad \rho_2 = \frac{Z_s - Z_r}{Z_s + Z_r}, \quad \rho_3 = \frac{Z_0 - Z_s}{Z_0 + Z_s}, \quad (11)$$

$$Z_q = \frac{\omega \mu_0}{\beta_q}, \quad q=0, r, s, \quad (12)$$

$$\beta_q = \sqrt{\omega^2 \mu_0 \epsilon_q - \left(\frac{\pi}{a}\right)^2}, \quad q=0, r, s, \quad (13)$$

where ρ 's are the elementary reflection coefficients at each interface, d 's are the media thicknesses, Z_q is the media impedance, β_q is the propagation constant and the subscript $q = 0, r, s$, for air, acrylic and simulant, respectively.

Using (7) and (10), a custom-written nonlinear iterative Matlab code is used to calculate the real and imaginary permittivities, ϵ' and ϵ'' .

2.6. Calibration factor measurements

To calculate the calibration factors for each orthogonal dipole, the probe is rotated about its axis in incremental steps of 60° (figure 3(b)). Isotropic data were recorded at different steps ranging from 5° to 60° increments, and it was empirically found that $\theta = 60^\circ$ is sufficient to recover the calibration factors with adequate precision. From the isotropic data, an anisotropy of less than $\pm 1\%$ was observed. From the voltage readings of each orthogonal

dipole, obtained from the probe isotropic scan, the calibration factors for each dipole are obtained by fitting the sum of the voltages to the squared magnitude of the theoretical value for the fundamental mode TE_{10} of the total electric field inside the tissue-equivalent liquid, (14). This method eliminates the need to perform a separate calibration procedure for each dipole [20]:

$$\frac{1}{P_{\text{net}}} \left[\frac{V_1}{k_1} + \frac{V_2}{k_2} + \frac{V_3}{k_3} \right] = \frac{4\omega\mu_0}{ab2\beta} \sin\left(\frac{\pi}{a}x_0\right) e^{z\alpha}. \quad (14)$$

2.7. Net power measurements

Figure 4(b) shows the power flow to and from the waveguide. The input power from the signal generator is amplified and fed through a coupler to measure the forward and reverse powers. To calculate the forward and reverse powers inside the waveguide, the losses in the coupler and cable must be considered. The forward power must be corrected for forward coupler loss C_f , coupler insertion loss C_i and cable loss L_b ; the reverse power must be corrected for reverse coupler loss C_r and cable loss L_b , (15)–(17)

$$P_{\text{for}} = P'_{\text{for}} - C_f + C_i + L_b \quad (15)$$

$$P_{\text{rev}} = P'_{\text{rev}} - C_r - L_b \quad (16)$$

$$P_{\text{net}} = P_{\text{for}} - P_{\text{rev}}. \quad (17)$$

The conductor loss in the waveguide due to finite wall conductivity is ignored at 900 MHz and 1800 MHz. The conductor losses for an aluminum waveguide is in the order of a hundredth of a dB.

3. Results

The system is validated using saline solutions at 900 MHz and 1800 MHz. Dielectric measurements and associated calibration factor calculations are performed on standard tissue-equivalent liquids at 900 MHz and 1800 MHz, respectively. Dielectric measurements are compared with the HP 85070C Dielectric Probe Measurement System.

3.1. Validation

A series of tests were performed to determine the complex permittivity of saline solutions. Table 3 shows the results for 900 MHz and 1800 MHz.

A saline solution at 0.5 salinity is 0.5% NaCl (salt) and 99.5% water. Another way of expressing concentration is called molarity. Molarity is the number of moles of a solute

dissolved in 1 L of solution. Saline solutions of known molarity are often used for the calibration of dielectric measurement apparatus.

3.2. Dielectric properties

Standard tissue-equivalent liquids were measured at 900 MHz and 1800 MHz. To ensure the repeatability of the measurement system, repeated measurements were performed using the same tissue-equivalent liquid at 900 MHz, and at 1800 MHz different measurements were performed for different tissue-equivalent liquids (table 4). The power return loss at the air/dielectric-slab interface is less than -8 dB at 900 MHz and 1800 MHz.

3.3. Calibration factors

E-field probes are calibrated in standard tissue-equivalent liquids that are used in SAR compliance measurements. The results for calibration factors at 900 MHz and 1800 MHz are shown in table 5. The calibration factors are measured at different power levels to ensure invariability.

4. Uncertainty analysis

The reported uncertainties are calculated from the curve-fitting procedures and the tolerances of the instrumentation used. Table 6 gives the reported instrumentation tolerances, curve-fitting errors, dielectric-slab measurement uncertainty and total uncertainties for the real permittivity ϵ' , imaginary permittivity ϵ'' and calibration factors k_i at 900 MHz and 1800 MHz. The uncertainties are calculated based on the 95% confidence level. The overall uncertainty calculations in SAR measurements are calculated by following the IEEE 1528 standard [4].

4.1. Dielectric properties

The dielectric parameters ϵ' and ϵ'' are calculated using the nonlinear expressions for the measured attenuation factor α and power reflectance $|\Gamma|^2$. Using Monte Carlo simulation [22], random scatter is added to the input parameters and the complex dielectric properties are solved at each step. The procedure is repeated around 10 000 times. From the resulting values for the real and imaginary permittivities, the uncertainties are evaluated. The uncertainty in liquid conductivity σ is directly proportional to the uncertainty in the imaginary permittivity ϵ'' , (4).

The sensitivities at 900 MHz in tissue-equivalent permittivity to power reflectance $|\Gamma|^2$, frequency f , waveguide dimension a , attenuation factor α and slab permittivity are calculated and shown in figure 5. The dielectric properties are most sensitive to variations in dielectric-slab permittivity as shown in figure 5(e). Therefore, accurate measurements [23, 24] of the dielectric slab used must be performed to ensure the accuracy of the measured dielectric properties of tissue-equivalent liquids.

4.2. Calibration factors

From (14), the calibration factors k_1 , k_2 and k_3 are inversely proportional to the electric field magnitude squared $|E|^2$. Since any changes in the electric field magnitude will affect all

calibration factors equally, (18) can be used to calculate the uncertainties in the calibration factors:

$$K = \frac{V_t}{|E|^2}, \quad (18)$$

where V_t is the total measured voltage and K is the consolidated calibration factor.

The uncertainty in K due to changes in the electric field magnitude squared $|E|^2$ [22] is

$$\left(\frac{\Delta K}{K}\right)^2 = \left(\text{UMF}_{|E|^2} \frac{\Delta |E|^2}{|E|^2}\right)^2, \quad (19)$$

where $\text{UMF}_{|E|^2}$ is the uncertainty magnification factor related to $|E|^2$ and is given by

$$\text{UMF}_{|E|^2} = \frac{\partial K}{\partial |E|^2} \frac{|E|^2}{K} = -1. \quad (20)$$

Therefore, the uncertainty in K is proportional to the uncertainty in $|E|^2$. The electric field sensitivity, $|E|^2$, due to angular frequency w , waveguide dimension a , real permittivity ϵ' and imaginary permittivity ϵ'' is

$$\left(\frac{\Delta |E|^2}{|E|^2}\right)^2 = \left(\text{UMF}_w \frac{\Delta w}{w}\right)^2 + \left(\text{UMF}_a \frac{\Delta a}{a}\right)^2 + \left(\text{UMF}_{\epsilon'} \frac{\Delta \epsilon'}{\epsilon'}\right)^2 + \left(\text{UMF}_{\epsilon''} \frac{\Delta \epsilon''}{\epsilon''}\right)^2, \quad (21)$$

where the UMFs are the uncertainty magnification factors and are given by

$$\begin{aligned} \text{UMF}_w &= \frac{\partial |E|^2}{\partial w} \frac{w}{|E|^2} \\ &= \frac{\pi^2 \beta + zw \mu_0 \sigma (a^2 w^2 \mu_0 \epsilon_0 \epsilon' - 2\pi^2)}{a^2 \beta^3} \end{aligned} \quad (22)$$

$$\begin{aligned} \text{UMF}_a &= \frac{\partial |E|^2}{\partial a} \frac{a}{|E|^2} \\ &= w^2 \mu_0 \varepsilon_0 a^2 \frac{-w^2 \mu_0 \varepsilon_0 a^2 \varepsilon'^2 + \pi^2 (\varepsilon' + \varepsilon'' z \beta)}{(a\beta)^4} \end{aligned} \quad (23)$$

$$\begin{aligned} \text{UMF}_{\varepsilon'} &= \frac{\partial |E|^2}{\partial \varepsilon'} \frac{\varepsilon'}{|E|^2} \\ &= \frac{1}{2} w^2 \mu_0 \varepsilon_0 a^2 \varepsilon' \frac{-w^2 \mu_0 \varepsilon_0 a^2 \varepsilon' + \pi^2 + w \mu_0 a^2 z \sigma \beta}{(a\beta)^4} \end{aligned} \quad (24)$$

$$\text{UMF}_{\varepsilon''} = \frac{\partial |E|^2}{\partial \varepsilon''} \frac{\varepsilon''}{|E|^2} = -z \frac{w \mu_0 \sigma}{\beta}. \quad (25)$$

Therefore, the uncertainty in $|E|^2$ depends not only on the uncertainties in w , a , ε' , ε'' and slab permittivity, but also on the value of the parameters themselves. Thus, the uncertainties in $|E|^2$ will vary with operating conditions. The sensitivities at 1800 MHz, for $z = 15$ mm, in calibration factors to real permittivity ε' , imaginary permittivity ε'' , angular frequency w and waveguide dimension a are shown in figure 6.

5. Conclusion

We introduced a system for precise dielectric property measurement and associated E-field probe calibration where a rectangular waveguide is utilized to generate an analytically known field inside a tissue-equivalent liquid [9, 10, 25, 26]. The use of waveguides has some clear advantages: no anechoic chamber shielding is needed to minimize multipath reflections of the calibration field or shield-radiated interference, the system is compact and the RF power needed is minimized. Furthermore, using the same waveguide for tissue-equivalent dielectric measurements and calibrating E-field probes in SAR measurements eliminate a source of uncertainty. The uncertainties of the measured values are within $\pm 3\%$, at the 95% confidence level. In addition, we clearly identified the system parameters that affect the overall uncertainty of the measurement system.

Acknowledgments

We would like to acknowledge the help of Dr Howard I Bassen and Dr Wolfgang Kainz, at the Food and Drug Administration, Center for Devices and Radiological Health. Additionally, we would like to thank Mr Bruce R Fleharty and Mr Randolph L Bidingar at the Food and Drug Administration, Center for Devices and Radiological Health, for their help in building some of the components used in this research. This work is supported in part by an appointment to the Research Fellowship Program at the Center for Devices and Radiological Health (CDRH) administered by the Oak Ridge Associated Universities (ORAU) through a contract with the US Food and Drug Administration (FDA).

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Figure 1. Dielectric measurement system setup consisting of a rectangular waveguide, tissue-equivalent liquid, E-field probe, and a data acquisition system and control.

Figure 2. E-field probe. The dipole sensors are in the narrow tip of the probe shown at the above right-hand side.

Figure 3.

(a) E-field probe scan along the waveguide z -axis and (b) E-field probe isotropic scan about its axis inside the waveguide.

Figure 4.
 (a) Power reflectance ϵ_1 and (b) net power calculation from forward and reverse power measurements.

Figure 5.

Change in complex permittivity ($\epsilon' = 40.62$, $\epsilon'' = 19.00$, $f = 900$ MHz) due to change in (a) power reflectance $|\Gamma|^2$, (b) frequency f , (c) waveguide dimension a , (d) attenuation factor α and (e) slab permittivity.

Figure 6.

Change in calibration factors due to change in (a) real permittivity ϵ' , (b) imaginary permittivity ϵ'' , (c) angular frequency ω and (d) waveguide dimension a . ($\epsilon' = 40.00$ $\epsilon'' = 13.98$, $z = 15\text{mm}$, $f = 1800\text{MHz}$.)

Table 1

Waveguide specifications at 900 MHz and 1800 MHz.

	WR975 (900 MHz)	WR430 (1800 MHz)
Waveguide internal width a (mm)	247.650	109.220
Waveguide internal height b (mm)	123.825	54.610
Frequency range (GHz)	0.75–1.12	1.70–2.60
Dielectric-slab width (mm)	50.715	25.358
Tissue-equivalent liquid depth (mm)	165.10	165.10

Table 2

Target dielectric values for standard tissue-equivalent liquids at 900 MHz and 1800 MHz.

	Relative permittivity ϵ'	Conductivity σ (S m ⁻¹)
900 MHz	41.5	0.97
1800 MHz	40.0	1.40

Table 3

Saline dielectric properties measured at 900 MHz and 1800 MHz.

	900 MHz						1800 MHz					
	Waveguide			HP probe			Waveguide			HP probe		
	ϵ'	ϵ''	ϵ'	ϵ'	ϵ''	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''
0.3 Salinity	78.7	16.3	77.0	77.0	17.0	13.6	77.4	13.6	78.0	13.0		
0.5 Salinity	78.3	24.3	77.0	77.0	24.0	15.9	77.5	15.9	77.0	17.0		
0.7 Salinity	76.5	31.1	77.0	77.0	30.0	20.0	76.9	20.0	76.0	21.0		

Table 4

Dielectric properties for standard tissue-equivalent liquids measured at 900 MHz and 1800 MHz.

	900 MHz						1800 MHz					
	Waveguide			HP probe			Waveguide			HP probe		
	ϵ'	ϵ''		ϵ'	ϵ''		ϵ'	ϵ''		ϵ'	ϵ''	
Measurement 1	40.62	19.00		40.26	19.88		39.86	13.59		39.88	13.56	
Measurement 2	40.57	19.12		40.26	19.88		39.47	13.56		39.43	13.66	
Measurement 3	40.26	19.09		40.26	19.88		40.95	13.64		40.54	14.01	

Table 5

Calibration factors measured at 900 MHz ($\epsilon' = 40.26$, $\epsilon'' = 20.88$, $z = 22.7$ mm) and 1800 MHz ($\epsilon' = 39.17$, $\epsilon'' = 14.69$, $z = 22.7$ mm).

	900 MHz	1800 MHz
Dipole 1 (mV (V m ⁻¹) ⁻²)	8.87	9.25
Dipole 2 (mV (V m ⁻¹) ⁻²)	8.54	8.97
Dipole 3 (mV (V m ⁻¹) ⁻²)	9.24	9.73

Table 6

Measurement and curve-fitting uncertainties used in the analyses at 900 MHz and 1800 MHz.

	Measurement uncertainty ($\pm\%$)	
	900 MHz	1800 MHz
Frequency	0.1	0.1
Forward power	1.2	1.2
Reverse power	1.2	1.2
Waveguide dimensions	0.1	0.1
Curve-fitting error	0.3	0.9
Dielectric-slab dimensions	0.1	0.1
Dielectric-slab permittivity	0.5	0.7
Real permittivity ϵ'	2.3	3.2
Imaginary permittivity ϵ''	1.3	2.1
Calibration factors k_i	1.5	1.8