Investigation of the effect of dehydration on tissue dielectric properties in ex vivo measurements

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Abstract
This paper discusses the impact of tissue dehydration on the dielectric properties of excised tissue samples. The effect of dehydration on the tissue surface has been characterized as a function of time after excision on freshly excised mouse liver. The dielectric properties of liver were measured over the frequency range of 500 MHz–20 GHz using an open-ended coaxial probe. Tissue samples were obtained from 7 athymic BALB/c Nude mice, and measurements were performed over the first 3.5 h post-excision at the tissue surface and in the middle of the sample (accessed via a small incision). The samples were kept in sealed containers between measurements to avoid excessive dehydration. The measured dielectric data show a change of more than 25% in both the real and imaginary parts of the complex permittivity over 3.5 h after excision. Results indicate the impact of tissue dehydration on the dielectric properties, and signify the importance of considering controls in the experimental design of ex vivo dielectric measurements.

Background
The dielectric properties of biological tissue are of significant importance in modeling and evaluating the energy deposition in a body exposed to radio-waves. Applications involving tissue dielectric properties range from the safety assessment of telecommunication systems to the characterization of medical diagnostic and therapeutic systems. Dielectric spectroscopy of biological tissue has been an active field of research over the past four decades, starting from the early studies by Schwan and Foster (1980). There has been a large number of studies reporting dielectric properties of various animal and human tissue over a wide frequency range of 10 Hz–100 GHz. In one of the most comprehensive studies, Gabriel et al (1996) reported the dielectric properties of a large number of biological tissues including freshly excised bovine and porcine tissue, human autopsy material, and human skin and tongue over a frequency range of 10 Hz–20 GHz. Dielectric data for various human and animal tissues reported in other studies (Foster et al 1979, Surowiec et al 1987, Peyman et al 2001, Schmid et al 2003, Lazebnik et al 2006, Abdilla et al 2013, Sasaki et al 2014) align with the data presented in (Gabriel et al 1996), which is widely used in electromagnetic modeling and assessment of specific absorption rate. Stuchly et al (1982) studied inter-species differences in dielectric properties of skeletal muscle, brain cortex, spleen, and liver tissue between 0.1 and 10 GHz, and reported a very small difference (within system uncertainty) between the same tissues of different species, which led researchers to believe that the data from animal studies can be generalized and used for human tissue modeling. In addition to healthy biological tissue, the dielectric properties of a wide range of cancerous tissue has also been dielectrically characterized. For example, a number of studies, (Chaudhary et al 1984, Surowiec et al 1988, Joines et al 1994, Lazebnik et al 2007, O’Rourke et al 2007, Sugitani et al 2014) characterized the dielectric properties of cancerous tissues that are being used in the development of medical diagnostic and therapeutic applications.

Most of the data on dielectric characterization of tissue are based on excised samples, where the time of measurement varies between 5 min and 5 h after excision from the donor body. These measurements provide dielectric data of tissue which is far removed from the normal physiological state. The data from ex vivo
measurements therefore does not account for factors such as blood perfusion, temperature, tissue dehydration, and ischemic effects (Foster and Schwan 1995). The factors influencing the dielectric measurements can be divided into two categories based on two stages of the tissue excision process: (1) bio-physiological impact of death on the tissue; (2) other factors affecting the physiological state of the tissue during and after excision, e.g. tissue dehydration, temperature variations, or any physical damage to tissue sample. The impact of death has been studied by Lofgren (1950) in the low frequency range (2 kHz–15 MHz) on rat kidney, where the electrical impedance of the kidney was measured in situ before and after the death of animal. A decrease of 50% of the baseline value in conductivity was observed 1 h after animal death. In the most recent study on rat liver by Farrugia et al (2016), the dielectric properties of rat liver over the microwave range of frequencies (0.5–40 GHz) were measured in situ before and after animal death. In this carefully designed experiment, no statistically significant difference was observed in the dielectric properties of liver before and immediately after animal expiry (within the first 6 min). In contrast to the results from Lofgren experiments, Farrugia et al measured the dielectric properties at the high frequency range which is mainly driven by water content in the tissue. A drop in conductivity at low frequency can be associated with flaccidity of tissue, especially in the low kilo Hertz range. Farrugia et al concluded that the differences in the in vivo and ex vivo dielectric properties cannot be associated with blood perfusion, so the other factors including temperature and tissue dehydration may contribute to these variations. In other studies (Kraszewski et al 1983, Lazebnik et al 2006, Peyman et al 2009), similar observations have been reported.

The impact of temperature on tissue dielectric properties has been well characterized in the literature. Lazebnik et al (2006) studied the effect of temperature on dielectric properties of bovine and porcine liver obtained from a local abattoir, and developed a temperature dependent model of the dielectric properties of animal liver. In another study (Chin and Sherar 2001), the effect of temperature on dielectric properties at 915 MHz was studied on bovine liver. The changes in the biological tissue due to external heating were observed and categorized as reversible and nonreversible. The temperature coefficients for reversible changes and the critical energy that activates the nonreversible changes were reported. Chin and Sherar also studied the temperature effects on rat prostate at 915 MHz, and presented the temperature coefficients in (Chin and Sherar 2004). Stauffer et al (2003) reported temperature coefficients of porcine, bovine, and human liver tissues over the frequency range of 0.3–3 GHz. Early studies by Schwan and Kay (1957), Johnson and Guy (1972), Schwan and Foster (1980) discussed the temperature effects on various biological tissue over the microwave frequency range, predominantly 0.3–10 GHz. Ji and Brace (2011) used a microwave ablation system to heat the liver tissue up to 100 °C, and measured the dielectric properties from 0.5 to 6 GHz using an open-ended coaxial probe. The temperature at various distances was measured and a sigmoidal model was fitted to the data. In summary, the temperature coefficient of various tissue over a broad frequency range has been evaluated and reported in literature.

The effect of tissue dehydration is the other most influential factor in the dielectric spectroscopy of tissue, and is perhaps the most challenging to characterize for biological tissue. There can be large variations in the tissue hydration state due to varying experimental conditions. Various factors such as, ambient temperature, exposure to air, temperature control techniques (to heat or cool), and time between excision and measurements can affect the hydration state of the tissue. The impact of tissue dehydration can mostly be observed on the surface of the tissue, while the inner structure remains well protected from the external conditions. One of the most commonly used measurement techniques in the microwave frequency range is based on the use of the open-ended coaxial probe, which is put into contact with tissue to measure the reflection coefficient of the material under test. Therefore, the dehydration of the tissue surface being measured has a larger impact on the measurements in the open-ended coaxial technique.

In this article, the impact of tissue dehydration over time is studied in the frequency range of 0.5–20 GHz. Dielectric measurements were performed using an open-ended coaxial probe on seven freshly excised mouse liver samples at time 70 (which is taken as 8 ± 3 min after excision due to slight differences in the excision and transportation time), 30 min (0.5 h), 90 min (1.5 h), 150 min (2.5 h), and 210 min (3.5 h). Four different sites on the liver sample were randomly selected for measurements, and two sets (or groups) of measurements were carried out on each site: (1) at the tissue surface; and (2) deep under the surface (accessed via a small incision). The data from the surface group are compared with those from the interior group. A comparison with ex vivo data on rat liver from Peyman et al (2001) and in vivo data from Farrugia et al (2016) is also presented.

The remainder of the paper is organized as follows: section 2 describes the source and handling procedures for the tissue samples, the measurement system, sample size and sensing volume, and uncertainty analysis of the measurement system. Section 3 presents the results and comparison with existing studies, while the conclusion and future work are presented in section 4.
Materials and methods

Tissue samples
All in vivo work was approved by the institutional Animal Ethics Committee (National University of Ireland, Galway) and Health Products Regulatory Authority of Ireland. Female athymic BALB/c Nude mice (Charles River Laboratories, n = 7), aged 6–8 weeks, weighing 25.6 ± 1.1 g (mean ± SEM) were used for this experiment. Animals were placed under terminal inhalation anesthesia and a terminal bleed performed by cardiac puncture. The liver was excised within 5–10 min using a ‘Y’ incision. The intact liver was removed by handle of the diaphragm, to avoid tissue damage. The dry liver was then placed in a snug-fitting sterile sealed container.

At the time of first measurement (8 ± 3 min after excision), the sample temperature was dropped to room temperature (~22 °C), and all the measurements were performed at room temperature. The ambient temperature is well-controlled in the Lambe Institute for Translational Research at National University of Ireland, Galway where the research was carried out; therefore, the sample (tissue) temperature during the measurements had relatively small variability. The temperature of the tissue samples was measured using an infra-red [Precision Gold N85FR] thermometer at each measurement, and recorded as 22 ± 0.8 °C.

Dielectric measurements
Measurements were performed using a slim-form dielectric probe (Keysight 85070E, Santa Rosa, CA, USA) connected to a vector network analyzer (Keysight E8362B), and reflection coefficient ($S_{11}$) was recorded at 201 discrete frequency points over 500 MHz–20 GHz. The $S_{11}$ parameters were converted to complex permittivity using Keysight material measurement software suite (Keysight N1500A). The open-ended coaxial probe is the most common method to measure the broadband dielectric properties of the biological tissue (Surovic et al 1987, Gabriel et al 1996, Peyman et al 2001, Chin and Sherar 2001, Stauffer et al 2003, Schmid et al 2003, Lazebnik et al 2006, Ji and Brace 2011, Abdilla et al 2013, Sasaki et al 2014). In order to measure the reflection coefficient of the tissue sample, a lift table (lab jack) was used to lift the sample under the open-ended coaxial probe. The tissue sample was pressed against the probe to achieve proper contact for surface measurements. The samples were kept in snug-fitting sterile sealed container during the measurements, and the container was opened only to perform a measurement at time 70, 30 min, 90 min, 150 min, and 210 min, and kept closed otherwise. For each tissue sample, the following two sets of measurements were performed at four randomly selected sites over the time (30 min, 90 min, 150 min, and 210 min after excision): (1) three repeated measurements at the surface of the liver tissue on selected site; (2) three repeated measurements just below the surface at the same site. An additional three measurements at the surface of each sample was carried out at time 70 (8 ± 3 min after excision). This measurement pattern resulted in a total of 189 broadband measurements. Figure 1 shows one of the liver samples during the measurements, where open-ended dielectric probe is put into firm contact with the tissue surface for measurements.

Sample size and sensing volume
Open-ended coaxial probes were originally designed for dielectric measurements of liquids and powders, where the probe must be immersed in the material under test for accurate results. A minimum immersion depth is often reported for a probe to achieve specified accuracy (Keysight 85070E—5 mm immersion depth) for a liquid. Considering the advantages of broadband measurements and being useful for in vivo measurements, the open-ended probe has become the preferred choice in broadband dielectric spectroscopy of biological tissue. The effective sensing volume of the open-ended coaxial probes for tissue measurements has been widely studied for various applications. A number of studies (Hagl et al 2003, Meaney et al 2014, Meaney et al 2016) assessed the sensing depth of the open-ended dielectric probe in the tissue. The average sample size in the study presented in this paper was 20 mm (minor axes) by 25 mm (major axis). The thickness of the sample varied from 3 to 9 mm from edges to the center. Repeated measurements on various randomly chosen sites on the tissue sample at a given time were found consistent, which can be seen in the results.
Uncertainty analysis

The slim form coaxial probe was connected directly to the VNA to avoid error due to cable movement. One port calibration was performed at the tip of the probe using three standards: a short (shorting block in Keysight 85070E kit); open (air); and load (de-ionized water). Accuracy of the measurement system was evaluated on 0.1 M NaCl solution (Honeywell chemicals, Fluka 35275), using the standard analysis technique described in (Gabriel and Peyman 2006). In the estimation of total uncertainty of the measurement system, repeated measurements were performed on a standard liquid to assess random and systematic errors. The error was calculated for each discrete frequency point in the measurement and averaged over the band. Table 1 lists the random and systematic errors in the system, assessed over 0.1 M NaCl solution at 22 °C. The accuracy was calculated as deviation from the reference data obtained from the Cole–Cole model presented in Peyman et al (2007). Repeatability in table 1 is a measure of the standard deviation of the mean. A relatively large error was observed in the imaginary part of the complex permittivity, resulting in a larger contribution to the combined uncertainty. Figure 2 shows a comparison of dielectric properties of 0.1 M NaCl solution measured in this study and the reference data from Cole–Cole model in (Peyman et al 2007). In order to produce a less cluttered plot, only 21 frequency points out of 201 (every tenth point) are shown over 500 MHz–20 GHz in figure 2. Measured data is found to be in agreement with the reference data with average error less than 2%. The average value of dielectric constant is slightly lower than the reference data, while it is higher in conductivity.

Results and discussion

The measured data (189 broadband measurements) were divided into two groups: (1) data from measurements at the surface of tissue at time $T_0$, 30 min (0.5 h), 90 min (1.5 h), 150 min (2.5 h), and 210 min (3.5 h) for all tissue samples (105 broadband measurements); (2) data from measurements in the middle of the samples for all measurement sites and for all tissue samples (84 broadband measurements). The tissue was fresh and well hydrated at first measurement ($T_0$), so only three measurements at the surface of the tissue were performed at three randomly selected sites. Table 2 summarizes the data distribution in the two groups. Data from the interior group was found to be stable over time with very small variation over time, and it is treated as reference. The surface group is further divided into five sub-groups, each representing the dielectric properties of tissue at various time instances which is affected by tissue dehydration.

| Uncertainty                        | Dielectric constant (%) | Conductivity (%) |
|-----------------------------------|-------------------------|-----------------|
|                                   | 0.5–20 GHz              | 0.5–20 GHz      |
| Repeatability (standard deviation of mean) | 0.22                   | 0.69            |
| Accuracy (deviation from reference)           | 0.53                   | 1.18            |
| Drift (systematic drift over time)             | 0.04                   | 0.07            |
| Cable movement                       | —                      | —               |
| Combined uncertainty                | 0.58                   | 1.37            |

Figure 2. Comparison of measured dielectric constant and conductivity of 0.1 M saline (verification liquid) with data from Cole–Cole model in Peyman et al (2007). The error bars show standard error of the measured data.
Measured dielectric properties at $T_0$ (8 ± 3 min after excision) from the surface group have been found to be within standard error of the mean of the reference data (interior-group); therefore, it is excluded from analysis. Effectively the change in dielectric properties at $T_0$ with respect to the mean of reference data was within the standard error, that leads to a conclusion that there is no statistical difference between dielectric properties at the surface of freshly excised liver tissue and the properties in the middle of the sample.

**Effect of tissue dehydration on dielectric properties**

The dielectric constant and conductivity of the liver tissue from the interior group (inside: 0–3.5 h) are compared with the data from the surface group (0.5, 1.5, 2.5, and 3.5 h), and mean and standard error are shown in figure 3 (dielectric constant) and figure 4 (conductivity). A significant change in both the dielectric constant (average >25%) and conductivity (average >30%) of the tissue has been observed as a function of time after excision.
Figures 5 and 6 show the percentage change relative to the interior group in dielectric constant and conductivity at time; 0.5, 1.5, 2.5, and 3.5 h. Although a general decreasing trend has been observed, the change in dielectric properties after 0.5 h is within measurement uncertainty (<3%). However, a significant change in both the dielectric constant and conductivity can be seen in the follow-up measurements at 1.5, 2.5, and 3.5 h. A decrease of >25% has been observed after 3.5 h. As the tissue temperature was well controlled during this experiment, these variations can be attributed to the loss of moisture (water content) in the tissue which is most evident at the surface of the tissue. It is important to note that the effect of surface dehydration can vary based on many factors, including but not limited to, ambient temperature, size of tissue sample, amount of water content in the tissue, tissue handling procedures, and exposure to air. Therefore, the results cannot be generalized to other biological tissue and experimental conditions. However, the results signify the extent of expected error in the ex vivo dielectric measurements due to tissue dehydration.

Comparison with previous studies
The data from the interior group was consistent over time with the average standard error being less than 7.5% in both dielectric constant and permittivity. No significant difference has been found between the data from the interior group and measurements taken at the surface of tissue at time T0, which was performed on freshly excised tissue. In order to understand the relevance of the data from this study in terms of tissue moisture, a comparison has been made with dielectric data of rat liver from in vivo measurements (Farrugia et al 2016) and ex vivo measurements (Peyman et al 2001). Figures 7 and 8 show a comparison of dielectric constant and conductivity of reference data (this study: interior group) with Farrugia et al (2016) and Peyman et al (2001).
The graphs shown are based on the data derived from Cole–Cole models presented in (Farrugia et al 2016) and (Peyman et al 2001) at body temperature (37 °C). Farrugia et al studied the correlation between in vivo and ex vivo dielectric properties and reported no significant difference immediately after animal expiry (if the temperature is kept constant). A decrease in both the dielectric constant and conductivity in this study compared to in vivo data from (Farrugia et al 2016) can be seen in figures 7 and 8. This difference can be attributed to tissue temperature differences in the studies (Farrugia et al 37 °C, this study 22 °C). Data from ex vivo measurements in (Peyman et al 2001) corresponds to mean values of dielectric constant and conductivity of rat liver tissue between 2 and 4 h after excision at 37 °C. As the temperature in both studies (Peyman et al 2001, Farrugia et al 2016) is the same, the decrease in the dielectric properties of rat liver is evidently due to loss of tissue moisture. The difference in dielectric properties of freshly excised tissue in this study and Peyman et al (2001) can be associated with tissue dehydration over time. It must be noted that this comparison ignores the temperature differences, which can effectively result in an increase in the dielectric properties and shift the data from this study up closer to that of (Farrugia et al 2016).

It is found that the interior of the tissue remains well hydrated and protected for a relatively long duration compared to that at the surface. Therefore, the measurements carried in the middle of tissue sample can be a better estimate of the true dielectric properties assuming that all other factors are well compensated.

**Conclusion**

In this study, the effect of dehydration on the dielectric properties of biological tissue has been characterized as
function of time. Dielectric properties of freshly excised liver samples from 7 athymic BALB/c Nude mice were measured at time 0, 30 min (0.5 h), 90 min (1.5 h), 150 min (2.5 h), and 210 min (3.5 h). The samples were kept in sealed containers to avoid excessive loss in tissue moisture, and temperature was kept controlled at 22 ± 0.8 °C. The measurements were performed on the surface of tissue at four randomly selected sites, and under the surface at the same points. The data from measurements inside the tissue samples were combined and used as reference for comparison with data from four time instances. An average decrease of >25% in both the dielectric constant and conductivity has been observed after 3.5 h of excision, which can be associated with tissue dehydration. Results of this study are in line with the established understanding of the dehydration effects, and a comparison with in vivo and ex vivo data from the literature shows the magnitude of expected error in the ex vivo data. The results indicate a significant decrease in dielectric properties with tissue dehydration, and signify the importance of considering proper controls in experimental design of the ex vivo dielectric measurements.

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Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

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References

Abdilla L, Sammut C and Mangion L Z 2013 Dielectric properties of muscle and liver from 500 MHz to 40 GHz Electromagn. Biol. Med. 32 244–52

Chaudhary S S, Mishra R K, Swarup A and Thomas J M 1984 Dielectric properties of normal & malignant human breast tissues at radiowave & microwave frequencies Indian J. Biochem. Biophys. 21 76

Chin I and Sherar M 2001 Changes in dielectric properties of ex vivo bovine liver at 915 MHz during heating Phys. Med. Biol. 46 197–211

Chin I and Sherar M 2004 Changes in the dielectric properties of rat prostate ex vivo at 915 MHz during heating Int. J. Hyperthermia 20 517–27

Farrugia L, Schembri Wismayer P, Zammit Mangion L and Sammut C V 2016 Accurate in vivo dielectric properties of liver from 500 MHz to 40 GHz and their correlation to ex vivo measurements Electromagn. Biol. Med. 35 365–73

Foster K R, Schepps J L, Stoy R D and Schwan H P 1979 Dielectric properties of brain tissue between 0.01 and 10 GHz Phys. Med. Biol. 24 1177

Foster K R and Schwan H P 1993 Dielectric properties of tissues Handbook of Biological Effects of Electromagnetic Fields vol 2 (Boca Baton, FL: CRC Press) pp 25–102

Gabriel C and Peyman A 2006 Dielectric measurement: error analysis and assessment of uncertainty Phys. Med. Biol. 51 6033

Gabriel S, Lau R W and Gabriel. C 1996 The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz–20 GHz Phys. Med. Biol. 41 2251

Hagi D M, Popovic D, Hagness S C, Boothe J H and Okoniewski M 2003 Sensing volume of open-ended coaxial probes for dielectric characterization of breast tissue at microwave frequencies IEEE Trans. Microw. Theory Tech. 51 1194–206

Ji Z and Brace C L 2011 Expanded modeling of temperature dependent dielectric properties for microwave thermal ablation Phys. Med. Biol. 56 5249–64

Johnson C C and Gay A W 1972 Nonionizing electromagnetic wave effects in biological materials and systems Proc. IEEE 60 692–718

Jones W T, Zhang Y, Li C and Jirtle R L 1994 The measured electrical properties of normal and malignant human tissues from 50 to 900 MHz Med. Phys. 21 547–50

Kraszewski A, Maria A S and Stanislaw S S 1983 ANA calibration method for measurements of dielectric properties IEEE Trans. Instrum. Meas. 32 385–7

Lazebnik M, Mark C C, Boothe J H and Hagness S C 2006 Ultrawideband temperature-dependent dielectric properties of animal liver tissue in the microwave frequency range Phys. Med. Biol. 51 1941

Lazebnik M et al 2007 A large-scale study of the ultrawideband microwave dielectric properties of normal, benign and malignant breast tissues obtained from cancer surgeries Phys. Med. Biol. 52 6093

Lofgren Borje 1950 The electrical impedance of a complex tissue and its relation to changes in volume and fluid distribution; a study on rat kidneys Acta Physiol. Scand. Suppl. 81 1–51

Meaney P M, Gregory A P, Epstein N R and Paulsen K D 2014 Microwave open-ended coaxial dielectric probe: interpretation of the sensing volume re-visited BMC Med. Phys. 14 13

Meaney P M, Gregory A P, Seppälä I and Lahtinen T D 2014 Microwave open-ended coaxial dielectric probe effective penetration depth determination IEEE Trans. Microw. Theory Tech. 64 915–23

O’Rourke A P, Lazebnik M, Bertram J M, Converse M C, Hagness S C, Webster J G and Mahvi D M 2007 Dielectric properties of normal human, malignant and cirrhotic liver tissue: in vivo and ex vivo measurements from 0.5 to 20 GHz using a precision open-ended coaxial probe Phys. Med. Biol. 52 4707

Peyman A, Gabriel C and Grant E H 2007 Complex permittivity of sodium chloride solutions at microwave frequencies Bioelectromagnetics 28 264–74

Peyman A, Holden S and Gabriel C 2009 Dielectric properties of tissues at microwave frequencies MTHR 54 (16) 453–74

Peyman A, Rezaadze A A and Gabriel C 2001 Changes in the dielectric properties of rat tissue as a function of age at microwave frequencies Phys. Med. Biol. 46 1617

Sasaki K, Wake K and Watanabe S 2014 Measurement of the dielectric properties of the epidermis and dermis at frequencies from 0.5 to 110 GHz Phys. Med. Biol. 59 4739

Schmid G, Neubauer G, Illievich U M and Alesh C F 2003 Dielectric properties of porcine brain tissue in the transition from life to death at frequencies from 800 to 1900 MHz Bioelectromagnetics 24 413–22
Schwan H P and Foster K R 1980 RF-field interactions with biological systems: electrical properties and biophysical mechanisms Proc. IEEE 68 104–13

Schwan H P and Kay C F 1957 The conductivity of living tissues Ann. NY Acad. Sci. 65 1007–13

Stauffer P R et al 2003 Phantom and animal tissues for modelling the electrical properties of human liver Int. J. Hyperthermia 19 89–101

Stuchly M A, Kraszewski A, Stuchly S S and Smith A M 1982 Dielectric properties of animal tissues in vivo at radio and microwave frequencies: comparison between species Phys. Med. Biol. 27 927

Sugitani T, Kubota S-ichi, Kuroki S-ichiro, Sogo K, Arihiro K, Okada M, Kadoya T, Hide M, Oda M and Kikkawa T 2014 Complex permittivities of breast tumor tissues obtained from cancer surgeries Appl. Phys. Lett. 104 253702

Surowiec A, Stuchly S S, Eidus L and Swarup A 1987 In vitro dielectric properties of human tissues at radiofrequencies Phys. Med. Biol. 32 615

Surowiec A J, Stanislaw S S, Barr J R and Swarup A A S A 1988 Dielectric properties of breast carcinoma and the surrounding tissues IEEE Trans. Biomed. Eng. 35 257–63