Temperature-dependent dielectric properties of lung.

Julian Bonello (1), Adnan Elahi (2), Lourdes Farrguia (1), Charles V Sammut (1), Martin O'Hollaran (2), Emily Porter (2) and Roberta Balduino (2)
(1) University of Malta, Department of Physics, Msida, Malta
(2) College of Engineering and Informatics, National University of Ireland Galway, Ireland

Abstract

In recent years, microwaves (MW) have been used as an alternative modality for cancer therapy. The main area of application so far has been liver cancer. However, MW hyperthermia has also started to be used for the ablation of lung tumours. Published data on dielectric properties of lung tissue are limited but essential for reliable treatment planning and MW applicator design. The data presently available on lung tissue are scarce at body temperature and, to the authors' knowledge, no data exists on how dielectric properties vary with increasing temperature during the ablation process. Our study addresses this issue by investigating the dielectric properties of excised ovine lung tissue over a temperature range of 21 to 90 °C and over the frequency range 0.5 to 8.5 GHz. The tissue samples were heated by two distinct methods: a MW oven and a MW thermal ablator. Room temperature measurements reveal a significant spatial variability in tissue dielectric properties. The study also shows that as the temperature increases, both the real and imaginary parts of the permittivity decrease with frequency and increasing temperature.

1. Introduction

The use of MW as an alternative source of energy to develop novel applications for treating different medical conditions has been studied for many years [1, 2, 3]. Tumour ablation by MW hyperthermia has the potential of becoming an important treatment method for lung cancer.

When using MW for cancer therapy, knowledge of the dielectric properties of the exposed tissues and how these vary with temperature is important. The literature contains many published studies on the dielectric properties of biological tissues at body temperature (see for example [4], [5] and [6]). However, investigations of the variation of dielectric properties with temperature have been mostly limited to liver tissue. Due to the lack of data available, the design of treatment planning and monitoring systems as well as optimisation of MW applicators is very challenging, as there is limited knowledge of how different tissues interact with MW with increasing temperature of the exposed tissue. The ultimate purpose of addressing this lacuna in available data is to help medical professionals and clinicians to develop more personalised treatment modalities as well as to assist in the design and optimisation of MW applicators for more precise and reliable energy deposition into the tumour region.

The dielectric properties measurement and heating techniques used in the present study are similar to those previously reported [7, 8]. Two techniques of heating the ovine lung samples were used; heating in a MW oven and with a MW thermal ablator.

2. Methodology

Freshly excised lung samples were obtained from a slaughter house close to the National University of Ireland, Galway, where the experiments were conducted, and taken directly to the laboratory. During every collection, three lung samples were obtained and sectioned into smaller samples measuring approximately 10 cm by 6 cm by 5 cm. The samples under study were all obtained from six-month old animals.

We used a Keysight open-ended coaxial probe (model number N1501A) connected to a Keysight E5063A vector network analyser (VNA) for the dielectric measurements. The frequency range investigated was from 0.5 to 8.5 GHz, over a total of 201 data points. The sample temperature was recorded with a Neopix Reflex thermometer prior to each dielectric measurement. The measurement setups used with the two heating techniques are shown in Figure 1, with (a) illustrating the setup used to measure the dielectric properties, and (b) with the MW ablator embedded in the sample at 90° to the coaxial probe.

Calibration was carried out with the standard three-step technique, with the probe in air (open circuit), then with the probe end shorted and finally with the probe immersed in a known standard liquid (deionised water in this case). In order to validate the calibration, the permittivity of 0.1 N NaCl solution was measured and the results compared to previously validated experimental values for this solution.

Prior to heating the samples, we carried out repeated measurements at room temperature with the probe placed at different points on the samples in order to investigate the spatial variability in the dielectric properties of the tissue (Figure 2). We then heated the samples in the MW oven, taking them out for measurement at intervals of between one and three minutes, depending on the recorded temperature rise. Measurements were carried out in the temperature range from 17 to 86 °C.

Some problems were experienced at the higher temperatures when the sample surface temperature was observed to drop quite rapidly, owing to the difference between sample and room temperatures. We therefore measured the tissue temperature immediately before and after each measurement, recording the average temperature and associating this with the respective measurement. In addition, at higher temperatures, we noticed the formation of water on the sample surface. So we used a swab to dry the surface before conducting the measurements.

Using a different set of samples that were heated by means of an in-house microwave thermal ablator, dielectric properties were measured with the tissue temperature varying between about 30 and 91 °C. In this case, the heating was observed to be more rapid. Since the measurements were carried out in the presence of the ablator, it was ensured that its distance from the measurement point was sufficient for it not to alter the penetrating field in the vicinity of the measurement probe.

The heating process with the ablator was carried out using 80 W of input power for 3 minutes. This heating method was selected after multiple configurations of power and duration were tested on similar scrap tissue. During the heating process the temperature was continuously monitored and dielectric measurements conducted every 15 seconds.

(a) (b)

Figure 1. (a) The setup used to measure the dielectric properties; (b) the setup used while heating the test sample with the MW thermal ablator.

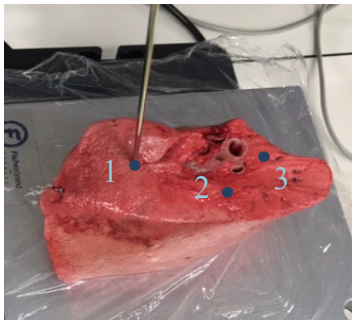

Figure 2. Example of sample under investigation with points at which measurements were taken.

3. Results

The results obtained at room temperature are displayed in Figure 3. These highlight the intrinsic inhomogeneity of the lung tissue under investigation, as both the permittivity and conductivity values varied significantly over the sample surface.

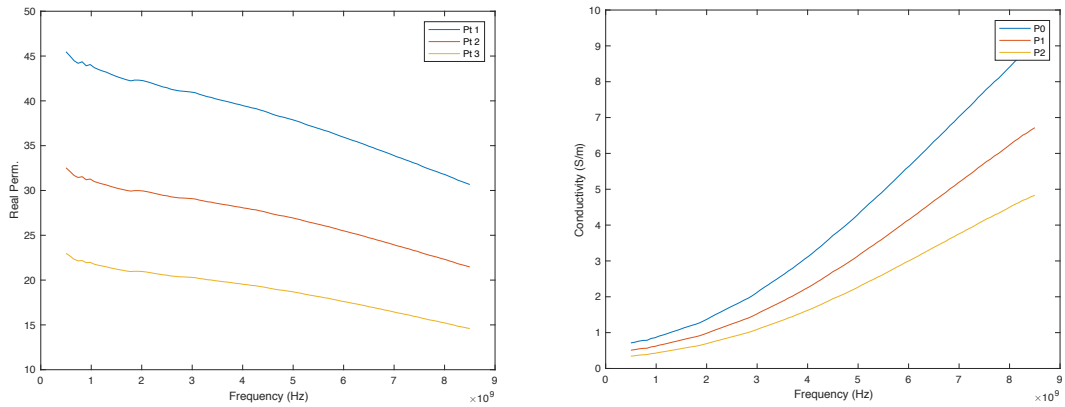

Figure 3. Room temperature measured dielectric properties of lung tissue at three different points on the sample as a function of frequency.

Figure 4 represents the measured permittivity as a function of frequency when one of the lung samples was heated in a MW oven. In general, the variation of the real and imaginary parts of the permittivity with frequency showed a similar trend at all temperatures, with lower overall values resulting as the temperature increased.

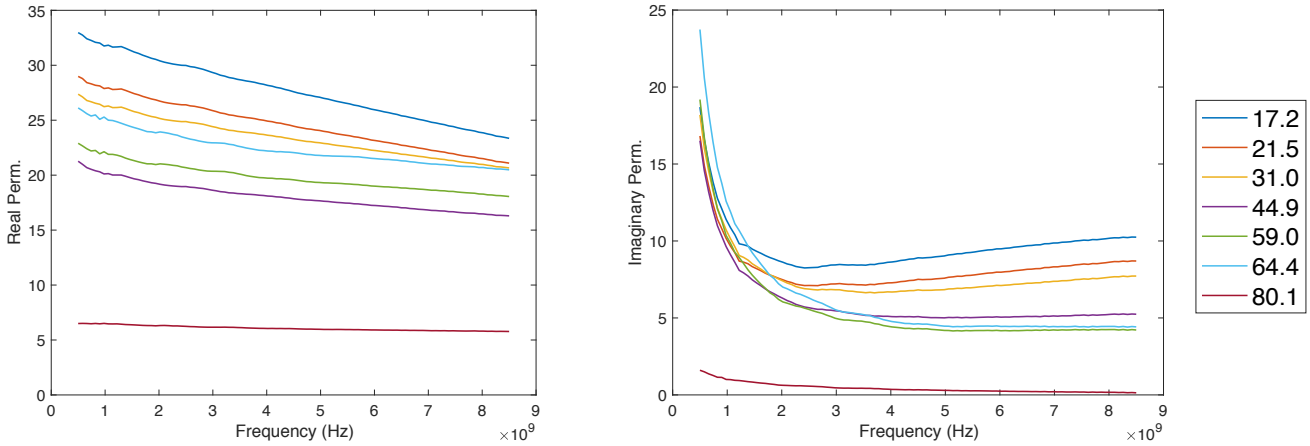

Figure 4. The measured dielectric properties of lung tissue as a function of frequency and temperature. (warmed using a microwave oven)

The third set of measurements shown in Figure 5 were obtained from a lung sample that was heated by means of the MW thermal ablator. Similar trends in the permittivity values with frequency and temperature were observed.

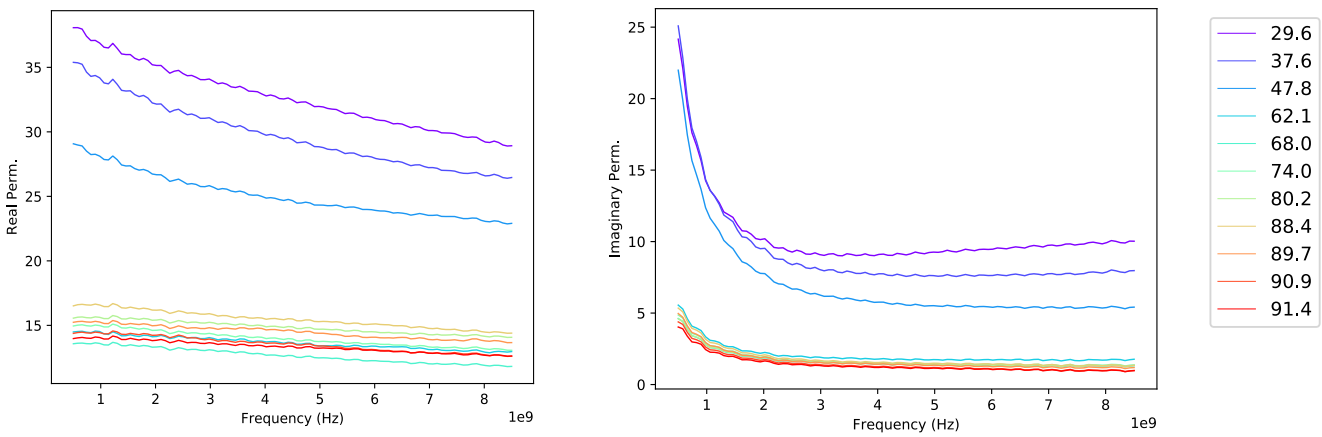

Figure 5. The measured dielectric properties of lung tissue as a function of frequency and temperature. (warmed using a microwave ablator)

The uncertainty calculation procedure used in this study was the one explained by Gabriel and Peyman [9]. In this method, the errors are split into Type A and Type B, and also corrected for drift of the VNA, measurement repeatability and deviation from the reference liquid. The standard deviation at particular frequencies was calculated for all the samples investigated at each temperature (± 2 °C).

At low temperatures, the measurement uncertainty in the real part of the permittivity varied between ± 9.6% at low frequency and ± 7.3% at high frequency, while in the imaginary part, the estimated uncertainty was ± 7.3% at low frequency and ± 3.3% at high frequency. At higher temperatures, the uncertainty was again higher at low frequencies (± 8.1% in the real and ± 7.6% in the imaginary) and reduced to ± 6.6% and ± 2.3%, respectively for the real and imaginary parts.

4. Conclusion

We measured the permittivity of ovine lung over a range of temperatures using two distinct heating methods. Our results do not indicate significant differences resulting from the two methods. The spatial variability in dielectric properties indicates tissue inhomogeneity. Further studies will focus on comparison between dielectric properties of different regions of the lung.

The results indicate that the permittivity decreases significantly with increasing temperature. Decrease in tissue water content could explain this decrease in permittivity, as it is expected that when the tissue heats up, water is driven out. However, the observed changes were not monotonic with temperature increase. This particular behaviour will be investigated further.

6. Acknowledgements

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7. References

1. Farrugia, L., P.Schembri Wismayer, L.Zammit Mangion, and C. V. Sammut. 2016. “Accurate in Vivo Dielectric Properties of Liver from 500 MHz to 40 GHz and Their Correlation to Ex Vivo Measurements.” Electromagnetic Biology and Medicine 8378(August):1–9.

2. Martellosio, Andrea et al. 2017. “Dielectric Properties Characterization From 0 . 5 to 50 GHz of Breast Cancer Tissues.” 65(3):998–1011.

3. Deshazer, Garron, Derek Merck, Mark Hagmann, Damian E. Dupuy, and Punit Prakash. 2016. “Physical Modeling of Microwave Ablation Zone Clinical Margin Variance.” Medical Physics 43(4):1764–76. Retrieved (http://www.ncbi.nlm.nih.gov/pubmed/27036574%5Cnhttp://scitation.aip.org/content/aapm/journal/medphys/43/4/10.1118/1.4942980).

4. Abdilla, Lourdes, Charles Sammut, and Louis Zammit Mangion. 2013. “Dielectric Properties of Muscle and Liver from 500 MHz–40 GHz.” Electromagnetic Biology and Medicine 32(2):244–52. Retrieved (http://informahealthcare.com/doi/abs/10.3109/15368378.2013.776436).

5. O ’rourke, Ann P. et al. 2007. “Dielectric Properties of Human Normal, 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 52:4707–19.

6. Gabriel, S., R. W. Lau, and C. Gabriel. 1996. “The Dielectric Properties of Biological Tissues .2. Measurements in the Frequency Range 10 Hz to 20 GHz.” Physics in Medicine and Biology 41(11):2251–69.

7. Lopresto, Vanni, Rosanna Pinto, Giorgio a Lovisolo, and Marta Cavagnaro. 2012. “Changes in the Dielectric Properties of Ex Vivo Bovine Liver during Microwave Thermal Ablation at 2.45 GHz.” Physics in Medicine and Biology 57(8):2309–27. Retrieved (http://www.ncbi.nlm.nih.gov/pubmed/22460062).

8. Lazebnik, M., M. Converse, J. H. Booske, and S. C. Hagness. 2006. “Ultrawideband Temperature-Dependent Dielectric Properties of Animal Liver Tissue in the Microwave Frequency Range.” Physics in Medicine and Biology 51(7):1941–55.

9. Gabriel, C., and Peyman, a. (2006). Dielectric measurement: error analysis and assessment of uncertainty. Physics in Medicine and Biology, 51(23), 6033–6046. Retrieved (https://doi.org/10.1088/0031- 9155/51/23/006)