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Conductivity and Permittivity Measurements of Children and Adult’s Hands Covering Mobile Communications Frequency Bands

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Abstract — This paper investigates the use of a simple open-ended coaxial line probe for measuring in vivo the relative permittivity and conductivity of human hands at microwave frequencies. In particular, we investigate how these properties are affected by the force with which the probe is pushed into the skin and the time over which the probe is in contact with the skin. Results show these two variables have a large influence on the measured results. We identify a suitable test procedure for use on a large scale volunteer study and present initial relative permittivity and conductivity results from more than 150 volunteers, ranging from ages 11 to 65.

1. INTRODUCTION

Smart phones have become more than simple communication devices; for many they are indispensable accessories capable of running sophisticated applications. The use of these smart phones by children is becoming more widespread. In this changing climate, possible health effects of radiation from mobile phones on children in particular, takes on an added importance. In order to assess the Specific Absorption Rate (SAR) in human tissue, the relative permittivity and conductivity of the tissue must be studied. These properties of biological tissues at microwave frequencies have been investigated over a number of decades [1–4]. Researchers have used live and dead animals as well as adult volunteers to measure the electrical properties of tissues.

Numerous full-body human phantom models are now available for EM simulations of SAR. Although a number of studies have developed mathematical functions to extrapolate child data from adult, actual measured conductivity and permittivity data for children is much harder to source.

As part of a large volunteer based study looking at how the hand holding a mobile phone affects the power absorbed in the head, this study evaluates the use of the open-ended coaxial line (OECL) probe technique for measuring palm relative permittivity and conductivity of human participants. First we investigate how the force with which the probe is pushed into the palm affects the relative permittivity and conductivity. With increasing force, we expect the blood to be forced away and the contact point to become closer to the underlying muscle, which will then change the dielectric properties. With the probe making contact with the palm, we also investigate how the measured results change with time. The aim is to develop a suitable measurement protocol that can be used on child and adult volunteers. Finally, we present relative permittivity and conductivity data collected from more than 150 participants and demonstrate how these properties change with age.

2. OPEN-ENDED COAXIAL LINE PROBE CONSTRUCTION AND CALIBRATION

The use of an open-ended coaxial line probe for measuring the dielectric properties of materials, especially liquids, has been studied for over three decades. Burdette et al. in 1980, were the first to demonstrate the use of an OECL probe [2]. The inner conductor of their probe protruded beyond the outer, in effect creating a miniature monopole. Further work by Athey et al. [3] and Stuchly et al. [4] eventually led to the more familiar flush OECL probe. Marsland et al. [5] carried out a detailed analysis of the use of an OECL probe for dielectric measurements. In [6], Blackham et al. presented the OECL probe technique with an added flange.

For our study, an OECL probe was produced by cleaving a RG-402 semi-rigid cable. A SMA connector was fixed to the other end. A flange was omitted from our probe design because there is limited space on the palm for taking a measurement, especially in the case of children. The natural creases in the skin also make it difficult to have a flange completely flush against the palm surface.

Calibration of the probe is a critical part of the measurement process. An Anritsu Lightning 37397D vector network analyser was set for CW signal at 1710 MHz (GSM 1800 frequency for channel 512) and calibrated at the end of the cable. Measuring a single data point minimises the
sweep time of the VNA allowing repeat measurements to be taken at short intervals. Once the OECL probe was connected to the cable, it was secured as shown in Figure 1 to minimise movement.

Figure 1: (a) Experimental setup for calibrating the probe weight; (b) photograph of the probe being used on a volunteer.

Calibration of the probe itself was conducted by measuring the complex reflection coefficient $\Gamma^*$ with three different calibration standards, namely open, short and deionised water. Open $\Gamma^*$ was recorded with the probe left open-ended in free space. Short $\Gamma^*$ was recorded with aluminium foil pushed against the cleaved end. Finally, the $\Gamma^*$ was measured with the probe dipped into pure deionised water to a depth of 3 cm below the surface. Kraszewski et al. [7] concluded that deionised water was the most suitable standard liquid for probe calibration based on a study of polar liquids. The depth to which the probe should be submerged is dependent on the diameter of the probe and in [8], Anderson et al. suggested that a 6.4 mm diameter probe only needs to be 6 mm below the surface of the liquid.

The complex permittivity of deionised water is calculated using the Debye Equation [10]

$$\varepsilon_w^* = \varepsilon' + j\varepsilon'' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau}$$

where $\varepsilon_w^*$ is the complex relative permittivity with $\varepsilon'$ and $\varepsilon''$ are the real and imaginary parts respectively. $\varepsilon_\infty$ is the relative permittivity at high frequencies and $\varepsilon_s$ is the static permittivity at low frequencies. $\tau$ is the relaxation time. From [11], $\varepsilon_\infty = 4.6$, $\varepsilon_s = 78.3$, and $\tau = 8.08$ ps. The complex relative permittivity ($\varepsilon_m^*$) and the effective conductivity ($\sigma_m$) of the material under test, in this instance the participant’s palm, is calculated from [5]

$$\varepsilon_m^* = -\frac{\Delta_{m2} \times \Delta_{13}}{\Delta_{m1} \times \Delta_{32}}\varepsilon_w^* - \frac{\Delta_{m3} \times \Delta_{21}}{\Delta_{m1} \times \Delta_{32}}$$

$$\sigma_m = \frac{\omega\varepsilon_0\varepsilon''}{\Delta_{ij}} = \Gamma_i^* - \Gamma_j^*$$

where $\Gamma_1^*$, $\Gamma_2^*$, $\Gamma_3^*$, $\Gamma_m^*$ are the measured complex reflection coefficients for the short, open, deionised water and material under test respectively.

3. FORCE AND SAMPLE TIME STUDY

The palm relative permittivity and conductivity was calculated by measuring the $\Gamma^*$ when the probe was placed on the palm of the volunteer. In order to change the force applied by the probe on the skin, the experimental setup given in Figure 1 was used. The point at which the clamp base pivots on the table was adjusted while the probe tip rested on an electronic scale. Markers were drawn on the crossbar of the clamp at locations where the readout on the scale corresponded to 50 g (0.49N) to 400 g (3.92N) in steps of 50 g (0.49N).

The VNA was set to display both the real and imaginary parts of the $\Gamma^*$. A digital video camera was placed in front of the display in order to record the change in $\Gamma^*$ over time. With the camera recording, the probe was placed on the centre of the volunteer’s palm ensuring the tip was not overlapping any of the natural creases in the skin. The video recording was made over a period of 50 seconds. The process was repeated with the clamp positioned at each of the markers on the crossbar, which corresponded to 0.49N to 3.92N. Following all the measurements, video editing software was used to tabulate the real and imaginary parts of $\Gamma^*$ at different periods. Readings were taken every 0.2 s for the first 2 s, every 0.4 s form 2 to 6 s and every 2 s from 6 s to 50 s.
3.1. Relative Permittivity and Conductivity Results

The calculated results for the relative permittivity and conductivity are show in Figures 2 and 3 respectively. It is important to note that the skin surface of the palm is not smooth. For an accurate measurement, the probe tip needs to be flush against the material’s surface. Even when the obvious large creases in the palm are avoided, there are small ridges in the skin that are unavoidable. These introduce tiny air gaps between the bottom of the probe and the surface of the skin and will thus reduce the calculated relative permittivity and conductivity results.

![Figure 2: Palm relative permittivity of participant at 1710 MHz measured over time with different probe effective masses.](image1)

![Figure 3: Palm conductivity of participant at 1710 MHz measured over time with different probe effective masses.](image2)

The volunteer reported that it was difficult to keep the hand perfectly still for 50 seconds. Small involuntary movements will have an effect on the measured reflection coefficient, and thus introduce ripples in the presented results.

In comparison to results presented in the literature for dry skin ($\varepsilon_r \approx 39, \sigma \approx 1.15 \text{ S/m}$) [12], our results appear significantly lower but when compared to dry palm results from the literature [13], our results are consistent.

Both relative permittivity and conductivity increase with time. Each plotted result shows a rapid change in the first 3 to 4 seconds followed by a gradual increase that tends to plateau. With increasing time, more blood is pushed away from the contact point and the underlying muscle relaxes which causes the probe to sink further into the palm. The gradual increase in the relative permittivity and conductivity may also be due to the small ridges in the skin flattening out, thus reducing the air gaps and improving the contact between the probe and the skin.

Both relative permittivity and conductivity increase with applied force. As the force applied by the probe increases, the displaced tissue engulfs the inserted probe tip. This has the effect of increasing the volume through which the fringing electric fields propagate. For an accurate measurement, all the electric fields emanating from the probe tip should propagate through the test material. We expected the relative permittivity and conductivity to increase with increasing force and this is observed in the measurements.

In order to minimise the escape of the electric fields into the air, the probe should be pushed firmly into the palm. However, there are obvious limits to the force that can be applied. A force of 3.92N (400 g) was uncomfortable to the participant and therefore is unsuitable for use in a volunteer study involving the public. Similarly, the time at which the VNA is sampled should be delayed to ensure the measurement has stabilised to but its final value, but this delay also has limitations. The participants are unlikely to endure long periods with the probe pushing into their palms.

4. VOLUNTEER BASED STUDY OF PALM PROPERTIES

Based on our above findings, an effective mass of 300 g (2.94N) was chosen as the most suitable test setup for the large scale volunteer study; results presented for 350 g and 400 g are similar to those taken with 300 g. Eight seconds was chosen as the delay period before recording the complex reflection coefficient off the VNA in order to reduce the discomfort caused.

Initial relative permittivity and conductivity data taken from more than 150 volunteers is presented in Figures 4 and 5. The results are grouped into 5 age brackets and for each bracket, an
average value has been calculated for the right and left hand. Each age bracket has at least 10 volunteers; the 20–30y bracket has the largest dataset with 79 volunteers.

Figure 4: Left and right hand palm relative permittivity plotted by age groups.

The general trend in both graphs is to show a decrease in palm relative permittivity and conductivity with increasing age. With increasing age, in general the skin becomes dryer and in the palm the skin becomes thicker and rougher. Therefore, we expect to see the conductivity and permittivity decrease with age. Somewhat surprisingly, in a majority of the age brackets, the right hand on average has a lower relative permittivity and conductivity compared to the left. We note that more than 90% of the volunteers were right handed. We could speculate that the right hand, as a result of being used more than the left hand, has thicker skin and thus lower relative permittivity and conductivity. There are likely to be unavoidable measurement variations between left and right hands caused by differing sweat and dirt levels as well as differing tension levels in the palm muscles during measurements. However, with further data collection from more volunteers, we can expect the influence of some of these uncontrollable variables to reduce.

5. CONCLUSIONS

In this study we have shown when measuring the relative permittivity and conductivity of the palm, the force applied to an OECL probe and the time at which the measurement is taken has a large impact on the results. Identifying the optimum force and time to collect the data is not a simple task. The time taken for the complex reflection coefficient measurement to reach a plateau is dependent on a large number of factors such as the suppleness of the skin and the tension in the underlying muscle. The effect of many of these uncontrollable variables can only be minimised by collecting a sufficiently large dataset and currently this is an on-going study. It is important to note that, the probe’s electric field penetrates not just the palm skin but also into the deeper tissue. Therefore the complex reflection coefficient captured during a palm measurement is the result of many electric field reflections from multiple tissue layers and as such, represents the relative permittivity and conductivity of a hand region rather than the skin alone.

REFERENCES


