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NOTE

Measurement of the electrical properties of human skin and the variation among subjects with certain skin conditions

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Abstract
In this study the dielectric properties are reported for human skin tissues over the frequency range 1–450 MHz at 36 °C. Healthy volunteers, collagen disease patients and dialysis patients are studied in order to investigate, primarily, the variability among (1) different regions of one individual, (2) the same region among different individuals and (3) skin conditions due to diseases. Considerable differences exist among the skin dielectric properties obtained from different regions of one individual body. Although region dependence is observed, larger variability is found even in the same skin region among individuals.

1. Introduction

The construction of an ultra-high field MRI scanner, with a whole-body magnet greater than 8 tesla, has just started in our facility. In ultra-high fields, acquiring images of high quality is known to be difficult because of the increase in operating RF frequency. Many factors such as dielectric resonance phenomena or the inhomogeneity of the RF field due to the coil's inherent properties cause degradation of image quality (Jin *et al* 1996, Barfuss *et al* 1990).

Wave impedance mismatching of the air–tissue interface may also cause RF field inhomogeneity within a body, especially where the skin surface forms uneven, complicated shapes.

Three things happen when an RF wave propagating in the air encounters a material such as the skin surface: the RF wave may be reflected, transmitted or absorbed. All three

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things are related to the dielectric properties of the material (Carl 1988). The human body is considered to be a dielectric structure constructed from various dielectric components. The reflection and diffraction pattern is very complicated where the surface forms a drastic curve and is likely to generate an inhomogeneous RF field within the body near the surface leading to the deterioration of image quality. This reflection and diffraction at the skin surface is restrained by filling up these structures with impedance-matched materials. The RF wave will be transmitted inside the skin effectively without causing serious reflection or diffraction.

The dielectric properties of human skin were measured. Many researchers have investigated the dielectric properties of biological tissue. The theoretical aspects and the main findings are reviewed by Pething (1984). Data collected over the past five decades are summarized by Gabriel *et al* (1996). Results of studies of several regions of human skin are also reported (Grant *et al* 1988, Tamura *et al* 1994). Healthy volunteers, collagen disease patients and dialysis patients are studied in order to investigate, primarily, the variability among (1) different regions of one individual, (2) the same region among individuals and (3) skin conditions due to diseases.

2. Material and method

Five healthy adult volunteers (males), two adult collagen disease patients (females) and seven adult dialysis patients (males) were studied. All of them were asked to participate in the study and admitted after informed consent was obtained according to the hospital guidelines.

Three regions of skin are mainly investigated on each subject at a temperature of 36 °C: ventral forearm, palm (thumb base) and ventral thumb. These regions were chosen to simplify taking measurements: they do not require the subject to adopt complex postures and thus the measurements could be made quickly and easily (this point is important especially for dialysis patients). Test tissues were attached to the coaxial probe while maintaining appropriate pressure during each measurement. Each region was measured at least three times.

In dialysis patients, the same region was re-measured immediately after the dialysis therapy was finished (within five minutes). The measured region was marked with a pen in order to set the probe at precisely the same place between the measurement and re-measurement. The dehydrated water volumes distributed vary widely among patients from 700 ml to 4500 ml. An open-ended coaxial probe method was used. This method was based on the determination of the input reflection coefficient of an open-ended coaxial probe placed against the test tissue. The input reflection coefficient depends on the dielectric properties of the tissue (Stuchly and Stuchly 1998, Gabriel and Grant 1989, Hewlett-Packard 2000).

To measure the input reflection coefficient of the probe, a computer-controlled system based on a vector network analyser was used. The system consists of an HP S-Parameter Network Analyzer 8753ES and an HP 85070C Dielectric Probe Kit, controlled through the HP–IB bus by an HP desktop computer. A standard calibration and error correction of the network analyser was used (air/open/distilled water) to obtain the highest possible measurement accuracy. The swept-frequencies were set in the range of 1–450 MHz and data points were obtained at 51 discrete frequencies, evenly distributed in the linear scale.

3. Results and discussion

Prior to carrying out the experiments described in the previous section, dielectric measurements of one of the authors were performed in several regions: palm (thumb base), temple (forehead), neck (thyroid) and abdomen (liver), and the results are shown in figure 1 as a relative

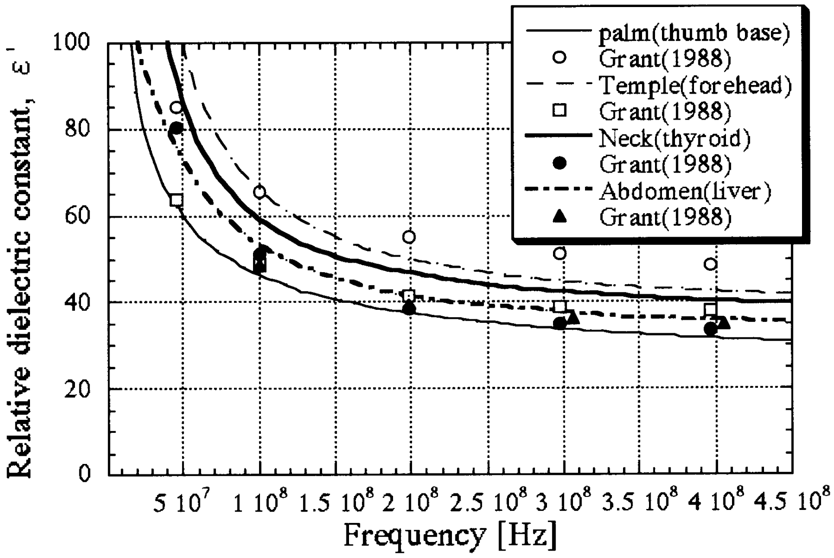

Figure 1. Comparison with previous data reported by Grant (1988).

permittivity. In addition to the author's experimental curves, the data previously reported by Grant at the same frequency range are also included for comparison (Grant *et al* 1988). Both sets of data were acquired using the same technique and confirmed not to have large spreads in measurement precision.

The results shown in the graph indicate that considerable differences exist between the skin dielectric properties obtained from different regions of one individual body. These wide range distributions reflect variations in tissue composition. Biological tissues are inhomogeneous and have considerable variability in structure and composition and hence in dielectric properties as shown. In addition, differences between subjects are also revealed. The variability of mean values at higher frequencies are ±20, 5, 8 and 3% in palm, temple, neck, and abdomen regions, respectively. Although results from some regions such as the abdomen agree, it is found that dielectric constant values of the same regions can have a difference of more than 20% over the entire range of frequencies between two subjects.

Dielectric properties of the ventral forearm region of five healthy subjects are shown in figure 2. Conductivity values were obtained from the expression $\sigma = 2\pi f \varepsilon_0 \varepsilon''$, where ε'' is the loss factor of complex permittivity, ε_0 is the dielectric constant of free space and f is the frequency of the applied electromagnetic field. The experimental data points shown at each frequency are the average set of three to five measurements on this region of each subject, and in all cases the inaccuracy of measurement is never greater than ±5%. This inaccuracy can be attributed to a combination of experimental error and the natural heterogeneity of the tissue. Measurement on distilled water produces both relative dielectric constant and conductivity values within 1.5% of the literature values at the lower frequencies and more accurate values (less than 1%) at higher frequencies. Thus, this decreased accuracy has evidently arisen from heterogeneity in the skin tissue rather than from experimental errors. The solid and broken curves represent the mean values of measurements on the five healthy subjects.

The spectra of relative dielectric constant ε' displays high frequency tail of the frequency-dependent decreases generally known as 'ε dispersion' up to about 200 MHz. At frequencies

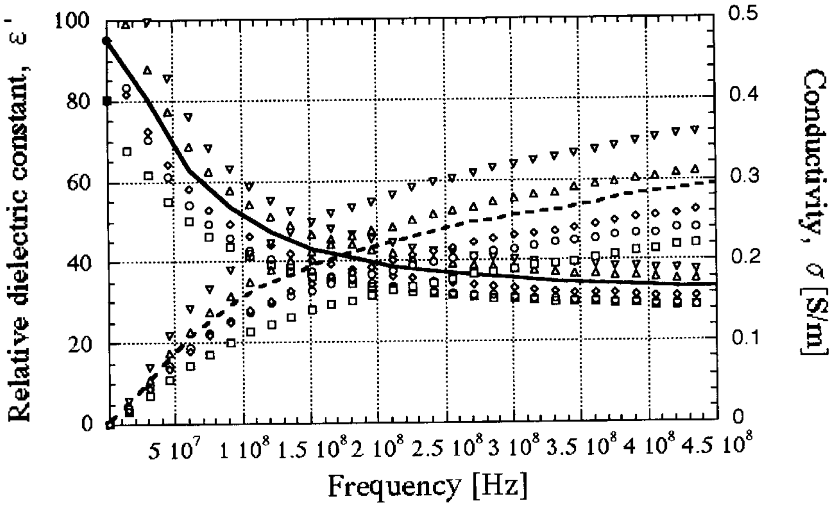

Figure 2. Dielectric properties of the ventral forearm of five healthy subjects, lines indicate mean value levels.

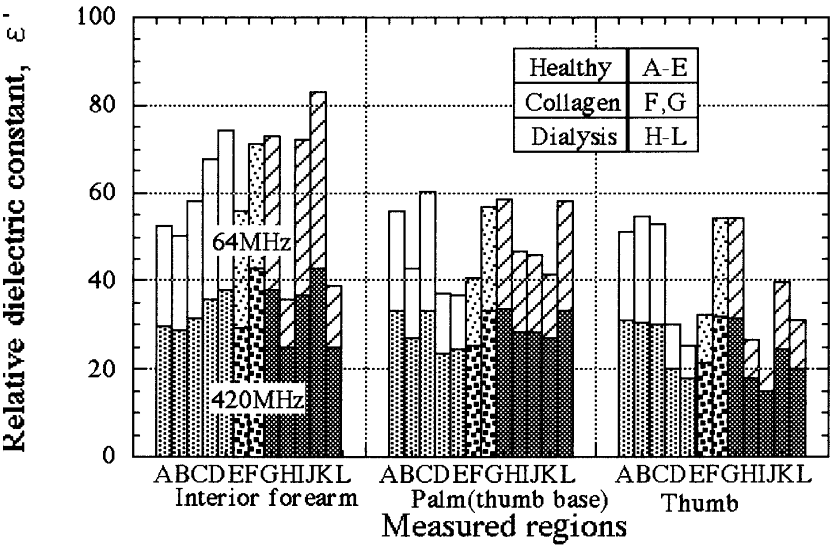

Figure 3. Comparison of relative dielectric constants among three kinds of subjects on three regions, at 64 MHz (upper) and 420 MHz (lower).

above around 200 MHz, the value of ε' decreases very slightly with frequency while the conductivity σ increases gradually.

The total spreads from the mean values among the five subjects are estimated to be about $\pm 19\%$ and 12% in the dielectric constant and $\pm 27\%$ and 24% in conductivity values at 64 MHz and 420 MHz, respectively.

Figure 3 represents the comparison of relative dielectric constants among three kinds of subjects on three regions at 64 MHz (upper) and 420 MHz (lower). The data sets of two dialysis patients are removed from here because their dry and wrinkled skin prevented the

Table 1. Comparison of dielectric properties among three kinds of subjects on three regions, at 64 MHz (upper) and 420 MHz (lower).

	64 MHz		420 MHz	
	ϵ'	σ (S m^{-1})	ϵ'	σ (S m^{-1})
Forearm				
Healthy(5)	$62 \pm 12(\pm 19\%)$	$11 \pm 3 \times 10^{-2}(\pm 27\%)$	$34 \pm 4(\pm 12\%)$	$29 \pm 7 \times 10^{-2}(\pm 24\%)$
Collagen (2)	$64 \pm 8(13)$	$17 \pm 7(41)$	$36 \pm 7(19)$	$36 \pm 12(33)$
Dialysis (5)	$60 \pm 23(38)$	$16 \pm 7(44)$	$34 \pm 9(26)$	$34 \pm 20(59)$
Palm				
Healthy	$48 \pm 12(25)$	$14 \pm 9(64)$	$28 \pm 5(18)$	$36 \pm 18(50)$
Collagen	$49 \pm 8(16)$	$12 \pm 5(42)$	$29 \pm 4(14)$	$31 \pm 9(29)$
Dialysis	$50 \pm 8(16)$	$10 \pm 2(20)$	$31 \pm 3(9)$	$28 \pm 5(18)$
Thumb				
Healthy	$40 \pm 15(38)$	$16 \pm 9(56)$	$25 \pm 6(24)$	$34 \pm 21(62)$
Collagen	$43 \pm 11(23)$	$11 \pm 7(64)$	$27 \pm 5(19)$	$29 \pm 12(41)$
Dialysis	$37 \pm 17(46)$	$10 \pm 7(70)$	$23 \pm 8(35)$	$24 \pm 14(58)$

probe from being attached to the skin completely and the air near the probe produces poor repeatability of experimental values.

No remarkable change was detected in the dielectric constant among the three groups. Region dependence of dielectric properties was observed. The spreads at lower frequency on the tail of dispersion are larger than at higher frequency. This tendency is generally observed in both dielectric constant and conductivity as shown in parenthesis in table 1. The mean and the spread values of both frequencies are listed in the table.

From our study and other previous reports, it is acknowledged that most of the relative dielectric constant values of the human skin are distributed in the range 20–50, while the conductivity values are in the range 0.1–0.8 at frequencies higher than 200 MHz.

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