Measurements of 1.8–2.7-GHz Microwave Attenuation in the Human Torso

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Abstract—**For the purpose of diagnostic application of microwaves, establishment of techniques to measure the signal transmission through the human torso is attempted. Leakage effects are the most troublesome measuring problem above 1 GHz because of high attenuation within the body. Swept-frequency measurement and close coupling between the flanged aperture antenna and the body assure that the results are free from leakage effects. Experimentally obtained attenuation constants of the abdomen and left thorax are almost the same as those of muscle tissues. In the thorax record, changes of attenuation caused by heartbeats or respirations are observed.**

I. Introduction

IN GENERAL, it is not easy to measure microwave transmission through the human body because of high attenuation and necessarily low signal strength. Also, leakage waves from the space between the transmitting antenna and the body diffract on the body surface, get into the receiving antenna, and mask or interfere with the transmitted signal. If we could detect the signal and avoid the leakage effects, we could have a diagnostic medium yielding physiologically significant information from inside the body such as heart dynamics, blood flow, or respiration [1]–[6]. Measurement of the transmission signal through the human body has been attempted below 1 GHz [1], [4], [6]. Shorter wavelengths would yield more detailed information from inside the body. However, no measurement in the human body has been achieved above 1 GHz. At these frequencies, the leakage effects make the measurement difficult since the attenuation in the body becomes very large.

This paper describes a measurement method at 1.8–2.7 GHz which avoids leakage effects. Close contact between the flange of the aperture antenna and the body surface avoids leakage, but loose contact or separation between the two introduces leakage. These aspects are manifested by using swept-frequency techniques. The possibility of leakage under the close-coupling condition is checked, and the leakage margin for the measurement is discussed.

II. Estimate of Microwave Attenuation Within the Human Body

It is well known that microwave attenuation in tissues increases remarkably above 1 GHz [3]. The attenuation in the human body at 2 GHz is evaluated theoretically as follows. For simplicity, we assume the object to consist of a single tissue of muscle, a conservative assumption, since muscle is one of the most strongly absorbing tissues.

The attenuation constant α is given by

$$\alpha = \omega\sqrt{\mu\varepsilon}\sqrt{\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)\Big/2} \qquad (1)$$

where ω is the angular frequency, μ is the permeability, ε is the permittivity, and σ is the conductivity. These constants for muscle at 2 GHz are given approximately by [3] $\mu = 1.3 \times 10^{-6}$ H/m, $\varepsilon = 4.4 \times 10^{-10}$ F/m, $\sigma = 1.8$ S/m; $\alpha = 49$ Np/m from (1). For a thickness (front–back) of the human torso of 0.18 m, the attenuation within the torso is about 77 dB. Actual attenuation in the human body may be less since it is not all muscle. However, impedance mismatches between adjacent tissue layers may serve to increase attenuation.

The following losses must be considered in determining attenuation within the body from a total attenuation between transmitting and receiving systems, for the attenuation is measured by the insertion-loss method. The power losses, which are actually measured, arising from the mismatch between each antenna and the body are 3 dB—a total of 6 dB. These values are in agreement with the theoretical reflection coefficient of the body [3], [7]. The loss resulting from separating antennas by 0.18 m is about 10 dB (Fig. 2, Part (B)).

III. Experimental Method

To minimize leakage effects, we employ flanged aperture antennas as transmitting and receiving antennas. When the flange is closely coupled with the body surface, the power, which propagates along the flange, is absorbed by lossy materials (skin, fat, muscle, and so on) without radiating outside the body or creeping into the receiver aperture. The antennas used in this experiment are aperture antennas of the standard waveguide (WRJ-2, inside dimensions 10.9 × 5.5 mm) with a flange (available for WRJ-2, dimensions 16.7 × 10.7 mm). The flange of the transmitting antenna is in contact with the bare (or thinly clad) body surface of the subject (normal male adult, torso thickness circa 18 cm) with the flange pressing on the body; the setup is similar for an identical receiving antenna. Separation or loose coupling (nonpress contact) between the flange and the body introduces leakage and elicits interference among leaked waves. The interference is easily demonstrated when the frequency is swept since the interferring phase varies. Accordingly, swept-frequency techniques are adopted in this experiment to indicate leakage.

The output of a sweep oscillator is fed to the transmitting antenna through an isolator, a variable attenuator for calibration, and a coaxial-line-to-waveguide transducer.

Manuscript received April 14, 1976; revised December 17, 1976.
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The transmitting power into the antenna is 12 dBm. The maximum power density incident on the human subject is about 0.5 mW/cm^2, as evaluated from its distribution inside the antenna. This figure is well below the standard safety level [8]. Power received at the receiving antenna, which is amplified (25 dB) by a wide-band microwave amplifier, is measured by a microwave power meter and recorded versus frequency from 1.8 to 2.7 GHz by using an X–Y recorder. The values of VSWR in the microwave circuit connections are below 1.3. This value does not yield significant error for the present measurement; on the contrary, leakage from the circuit connections, transmission cables, or components are harmful for the measurement. Hence semirigid cables are used for the transmission lines, and the circuit connections and components used are specially designed for preventing leakages.

The experiment is conducted in the ordinary laboratory. The coupling between the antenna and body is kept close and hence ambient reflecting objects do not influence the result. On the reference experiment (Fig. 2, part (B)), removal of the body), ambient reflections are obstructed by using microwave absorbers.

IV. Experimental Results

Coupling between the antenna and body surface critically affects the result. Fig. 1(a) is obtained from the right thorax when close contact between the flange and the body is maintained. Respiration is stopped during the recording run. The decaying characteristics of the received power agree with the attenuation properties of the biological materials [3], [7]. The ripples accompanying the curve are mainly caused by heartbeats (rapid changes) and the transmitting characteristics (slow fluctuations) of the signal generator. Fig. 1(b) shows a faulty measurement owing to leakage effects when the coupling between the flange and the body is loose; the results depart from those shown in Fig. 1(a) above 2 GHz. Fig. 1(c) shows the results when the flange is 0.5 cm away from the body surface. The attenuation characteristics of the biological materials are scarcely recognizable and strong peaks appear owing to interference among leaked waves; a slight movement of the torso or of a reflecting object around the body violently changes the results and masks the transmitted signals.

Fig. 2, part (A) shows the results of the abdomen and the thorax when the leakage effects are excluded by close coupling. Fig. 2, part (B) is given for the control, when the subject is removed from the measurement system. The attenuations in the abdomen and the left thorax are of the same order; the right thorax shows a decrease of over 10 dB.

Heartbeats and respirations modify the bulk attenuation. In the left-thorax recording, these modifications are clearly observed. Rapid and slow fluctuations are elicited by heartbeats and by respirations, respectively. The right-thorax record is almost the same as in Fig. 1(a). In the abdominal recordings during which the respiration is stopped, there is no contamination by heartbeat effects. Instead, crude attenuation properties of the body seem to contain the frequency dependence of the transmitting power.

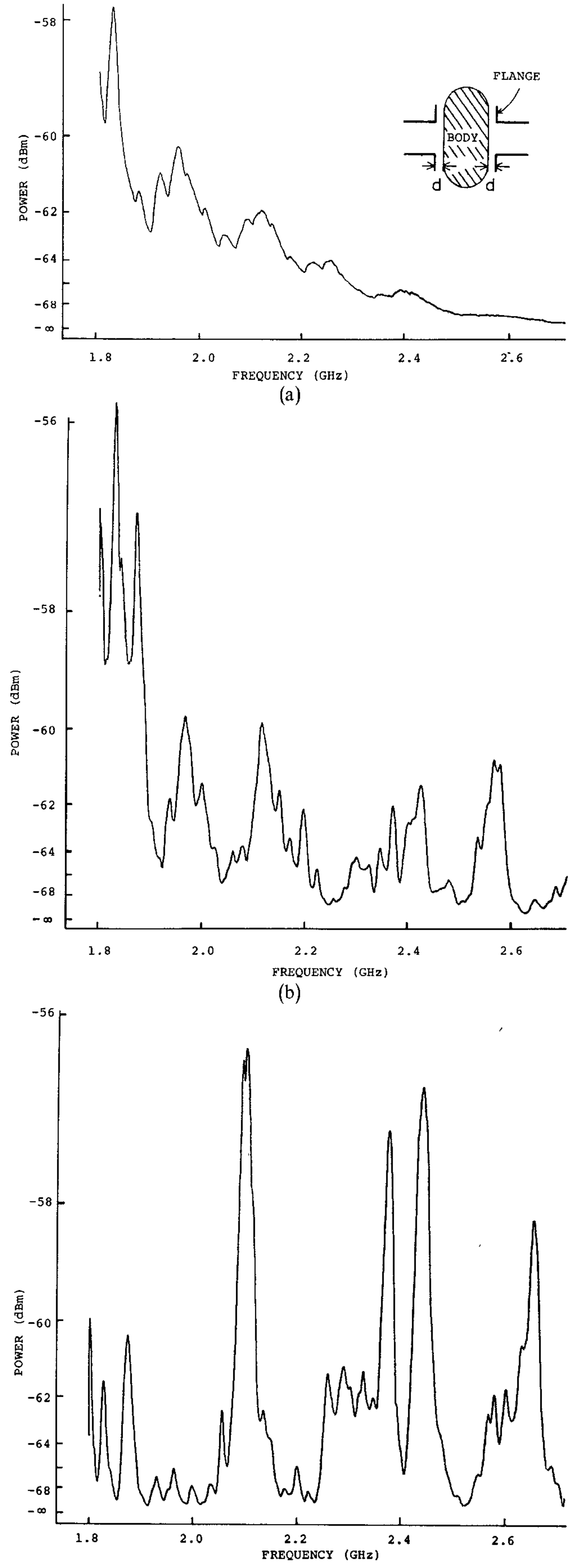

Fig. 1. (a) Close coupling ($d = 0.0$ cm). Sweep time: 20 s. (b) Loose coupling ($d \simeq 0.0$ cm). Sweep time: 20 s. (c) 0.5-cm separation ($d = 0.5$ cm). Sweep time: 20 s.

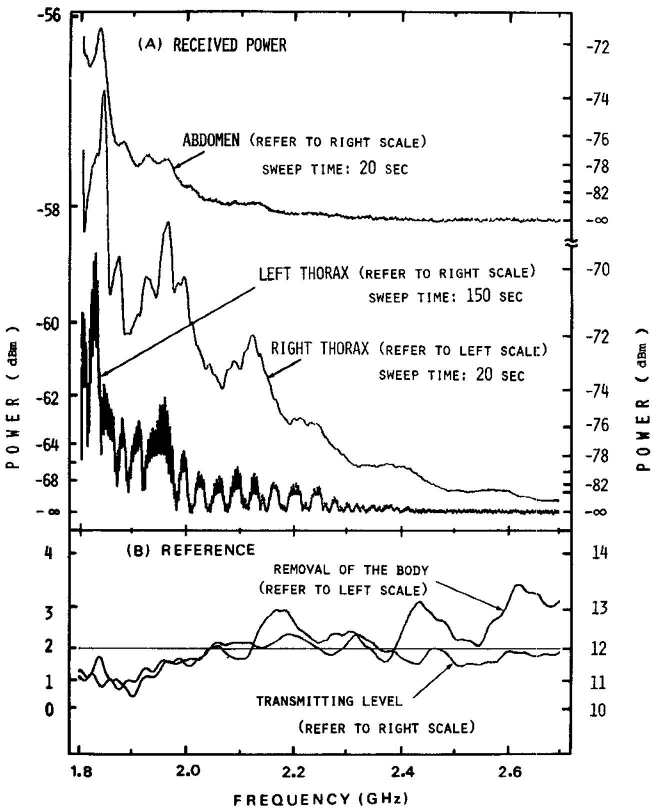

Fig. 2. Attenuation properties in the human torso.

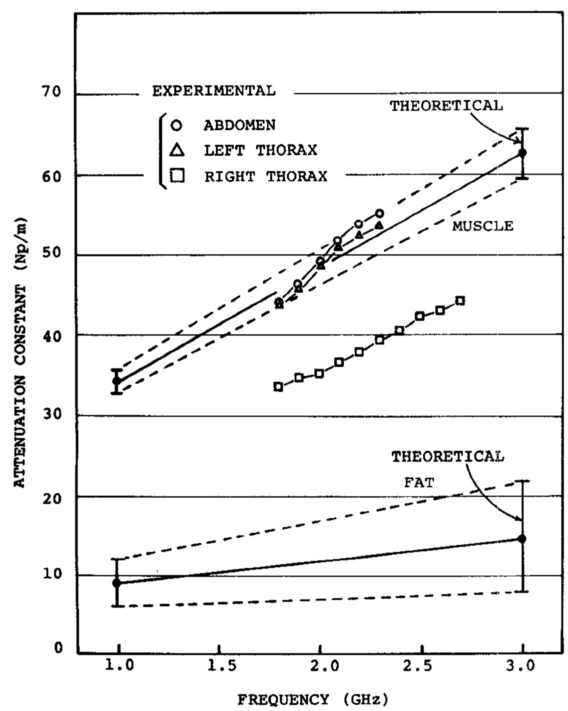

Fig. 3. Measured attenuation constants in the human torso.

Fig. 3 shows the attenuation constants calculated from the result of Fig. 2, in which averaged levels of fluctuation in the curve are adopted in the calculation after correcting the mismatch loss between the antenna and the body. The reference records are used to determine the attenuation within the body. The theoretical values are calculated from the constant table given in [3] by means of linear interpolation since the values between 1 and 3 GHz are not presented in the table. Because of the wide variation of the value at each frequency the mean values are shown by solid lines. Dashed lines indicate their limits. The attenuation constants of the abdomen and left thorax are the same as those of muscle tissues. The constant of the right thorax is smaller than that of muscle, but much larger than that of fat, implying that the attenuation in the right thorax is mainly caused by lung tissues. The upper limit of measurable frequency in the abdomen and left thorax is about 2.3 GHz with the available equipment, since transmitted signal levels in them fall below the sensitivity of the receiving system above 2.3 GHz.

V. Effects of Leakage

Close coupling between the antenna flange and the body surface successfully avoids the leakage effects; however, the possibility of leakage around or through the body surface must be checked further. We placed the receiving antenna at the incident side of the body about 1 m from it and measured power radiated (or reradiated) around the body. When the transmitting antenna is closely coupled with the body, the received power indicates about 30–40 dB of attenuation. These amounts, though they have wide variation owing to ambient conditions, increase as the receiving antenna is moved to the back of the body. At the opposite side of the transmitting antenna, they are of the order of the transmitted signal level, i.e., 70–80 dB, as the receiving antenna gradually falls into the loose-coupling condition. That does not necessarily measure the precise attenuation within the body since waves may creep into the receiving antenna from the space between the antenna and the body and interfere with the transmitted waves, as already shown in Fig. 1(b). Here, when we press the flange on the body surface (close coupling), no waves coming from the outside of the body into the antenna are observable (Figs. 1(a) and 2, part (A)). These unobservable leakage signal levels are also checked separately from the transmitted signal under the close-coupling condition. For this purpose, a shielding cloth (NASLON, EL-8002; Meisei & Co., Ltd., Tokyo), cut to the same size as the flange, is used to stop the transmitted waves from getting into the receiving antenna. This cloth is made of a mixture of ordinary textile fibers and stainless-steel fibers with an 8-μ diameter (20 percent by weight of the whole), and the shielding effect on the 2-GHz microwave is about 30 dB. In these tests, we cannot receive any microwave signal, leaked or transmitted, in the present receiving system. Through the above experiments, it is estimated that the close-coupling condition has over a 10-dB margin for the leakage at 2 GHz. This will make measurements at a higher frequency possible by means of a more sensitive receiver. These discussions are confirmed by using several subjects (male and female adults). As a conclusion, it is considered that the above results are useful in the application of microwave radiation as a diagnostic tool.

Acknowledgment

The author wishes to thank Prof. Z. Abe of the Research Institute of Applied Electricity, Hokkaido University, for useful discussions.

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