Radiometric Technique for Measuring Changes in Lung Water

M. F. ISKANDER, MEMBER, IEEE, C. H. DURNEY, SENIOR MEMBER, IEEE, T. GRANGE, AND C. S. SMITH

***Abstract* —In this paper, we describe a new approach to continuous, noninvasive monitoring of changes in lung-water content based on radiometry. It is shown theoretically, as based on a planar model of the lung, that a one-percent change in lung-water content corresponds to a 0.260-K change in brightness temperature, which is within the detection sensitivity of available radiometers. Practically, taking into account reflections at the tissue interfaces and attenuation in the chest wall, it is estimated that it is possible to detect a three to four-percent change in lung-water content. Initial experimental measurements at 1 GHz also have shown promising results. Some of the basic problems associated with the adaptability of the radiometric technique for clinical use have been identified and are discussed along with suggested solutions.**

I. Introduction

The importance of lung-water measurement hardly needs justification since many medical abnormalities and surgical treatments of the thorax are associated with pulmonary edema—increased water in the lungs [1], [2]. The available techniques to measure lung water are lacking adequate sensitivity, and it often is not possible to monitor early changes in the status of the lung, which is a critical need in medical diagnostics. Some of the available techniques are also elaborate and invasive, are associated with excessive levels of radiation, and are limited to specialized treatment centers [1]. There is, therefore, a great need to develop a simple, noninvasive, passive (no external radiation used) technique that is also suitable for continuous monitoring of changes in lung-water content [3]. In this paper, we present a new approach, based on radiometric techniques, for measuring changes in lung-water content. Results of our initial theoretical and experimental feasibility studies are presented. These results generally show that the method is promising for detecting early and small changes in lung-water content, but further work is still needed to develop the technique for clinical use.

II. Theoretical and Experimental Feasibility Studies

A radiometer measures the electromagnetic radiation emitted by the body. At moderate temperatures, the emitted microwave radiation is measured in terms of the brightness temperature T_B which is given for an electrically thick region by

$$T_B = \underline{e}T \tag{1}$$

where $\underline{e}$ is the emissivity of the body and T is the thermodynamic temperature of the body. Variations in this expression to account for the finite thickness of the lung region, particularly at lower frequencies, are described elsewhere [7]. More important, however, is that (1) simply indicates that the intensity of the emitted radiation is directly proportional to the body temperature as well as to its emissivity $\underline{e}$. The emissivity $\underline{e}$ generally varies according to the body's nature, orientation, composition, and surface conditions. For a planar model of the lung, assuming that the emitter fills a flat half space, the emissivity at normal incidence is given

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The authors are with the Department of Electrical Engineering, University of Utah, Salt Lake City, UT 84112.

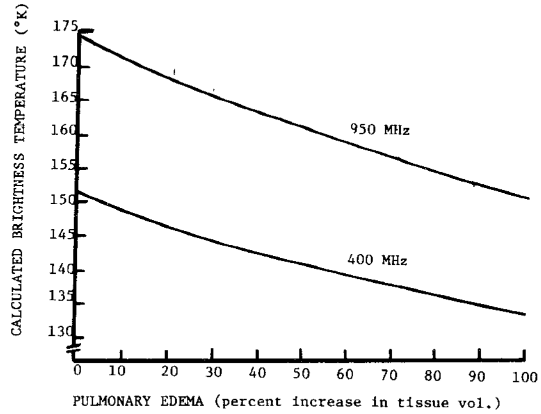

Fig. 1. Calculated brightness temperature of the microwave radiation emitted from the lung tissue versus degree of pulmonary edema

by

$$\underline{e} = 1 - \left| \frac{1-\sqrt{\epsilon^*}}{1+\sqrt{\epsilon^*}} \right|^2 \tag{2}$$

where the second term in the above equation is the Fresnel reflection coefficient, and ϵ^* is the complex permittivity of the emitter (lung). To calculate the variation in the brightness temperature as a function of changes in lung-water content, we used the following approximate formula to estimate the variation of the complex permittivity of the lung as a function of the changes in its water content [4], [10]:

$$\epsilon_{\text{lung}} = F_B \cdot \epsilon_{\text{blood}} + F_T \cdot \epsilon_{\text{tissue}} + F_A \epsilon_0$$
$$\sigma_{\text{lung}} = F_B \cdot \sigma_{\text{blood}} + F_T \cdot \sigma_{\text{tissue}}.$$

Values of the fractional volumes F_B, F_T, and F_A of the three basic components of the lung, namely blood, tissue, and air, are estimated for an adult male subject based on available data [4]. By such calculations of the complex permittivity, we related the changes in the body's emissivity $\underline{e}$ to changes in lung-water content by (2). In utilizing these changes in $\underline{e}$, we were able to calculate the variation in the brightness temperature that occurs with changes in lung-water content, as shown in Fig. 1. From Fig. 1, it is clear that changes in lung-water content significantly change the calculated emissivity, and hence the brightness temperature, as measured by the radiometer. Although these results show that a one-percent change in lung-water content corresponds to 0.26°K change in T_B, which is well within the detection capability of currently used radiometers (usually 0.1°K), such an optimistic estimation should be moderated by the effect of reflections at the lung–muscle (chest wall) interface and the wave attenuation through the 2 to 3-cm layer of the high-conductivity chest wall. If a planar model of the thorax consisting of three layers (including the lung), if a 2 to 3-cm-thick layer of high-conductivity chest wall, and if the skin are all considered, the change in the brightness-temperature-related flux of microwaves received by the radiometer antenna will be different from the true contribution originating in the lung region. According to the radiative transfer equation [11], these two quantities are related by the transmission coefficients at the interfaces between the various layers and by the attenuation in each conductive layer [7]. Assuming an EM field reflection coefficient Γ of 0.5 between the lung and chest wall tissues [5], and 60 to 70-percent attenuation in the chest-wall layer in the frequency range from 400 MHz to 1 GHz,

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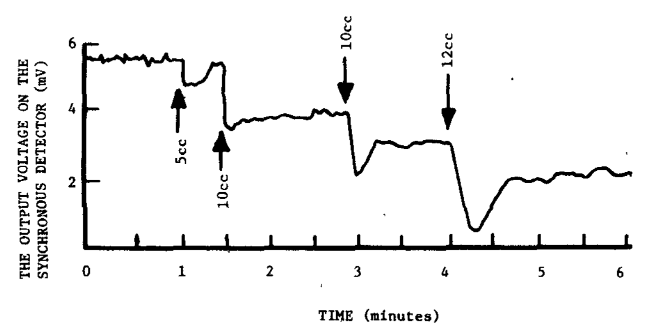

Fig. 2. Radiometric response to injections of water in a model of the human thorax. The model is a gray-body radiator whose emissivity, and hence emitted noise, decreases as the volume of water increases. A standard, 1-GHz Dicke radiometer [7] was constructed and used in these measurements.

it easily can be shown that available radiometers would still be capable of detecting changes in lung-water content as small as 3 to 4 percent, even by a conservative estimate. It might be worth emphasizing that, in our present application of measuring changes in lung-water content, there will be no major drawback from utilizing frequencies at 400 MHz or even lower. Although it is true that the use of radiometry for detecting breast tumors has been limited by the inability of the radiometer antenna to detect small tumors, a similar difficulty would not be expected in using radiometry to monitor changes in lung-water content because an average measurement over the region of the entire lung would provide very useful information. However, radiometry probably would not be very useful for measuring the spatial distribution of lung water for the same reasons that it does not detect small breast tumors.

We also constructed a 1-GHz Dicke receiver-type radiometer [6], [7] and used it to conduct experiments on models. Although the basic components of this radiometer are standard [7], specific characteristics of our 1-GHz radiometer are published in a separate paper [8]. It should be mentioned, however, that the temperature sensitivity of our radiometer is 0.3°C. This sensitivity can certainly be improved by adopting certain state-of-the-art procedures, such as enclosing the solid-state components in a constant temperature enclosure, and the design of a thermal comparator of precisely known and controlled temperature [9]. The geometry of the planar, tissue-simulating model consists simply of a flat synthetic muscle layer of approximately 0.25-cm thickness and two rectangular sponges, each of 2-cm thickness. A punctured tube for injecting water was sandwiched between the two sponges. All temperatures of the antenna, tissue phantom, and the injected water were controlled to a constant value equal to the room temperature. We used a 3×3-cm^2 open-ended ridged-waveguide receiver to detect the emitted radiation. This antenna was found adequate since it provides a broad-band matching to the model (or to the human body) and is also compact without requiring dielectric loading, which makes it easy to control its temperature and minimize the temperature gradient between the human body and the antenna. This, as well as other advantages of using the ridged-waveguide antenna, are described elsewhere [8]. Our experimental results are shown in Fig. 2, which clearly illustrate that the injection of small amounts of water in the lung region beneath the chest-wall layer resulted in an immediate and definite change in the radiometric signature. Equally important, the output signal tends to reach a new steady-state level after each injection. The peak that occurs after each injection is due to the initial burst of water, which slowly diffuses into the sponge model of the thorax. It also should be noted that the data presented in Fig. 2 provide representative examples of the many results we obtained using the 1-GHz radiometer.

III. Discussion and Conclusions

We have investigated a new approach for measuring changes in lung-water content based on radiometry. Based on a simplified model of the lung, it is theoretically shown that it is possible to detect a three to four-percent change in lung-water content. The initial experimental experience with the use of these measurements at 1 GHz also has shown promising results.

Before this technique can be adopted for clinical use, however, several basic problems should be investigated further and solved. For example, the tradeoff between low-frequency detection to achieve increased depth and high-frequency detection to get increased resolution should be studied. A more important problem, however, is that the stronger radiation produced by the surface tends to swamp out the weaker radiation emitted from the lung. This problem is particularly important because of the likely variation of the skin temperature during the experimental measurements. To overcome this problem, we are investigating the use of two or more simultaneous measurements at frequencies separated by at least one octave so we can measure surface emissions separately at the higher frequencies and use these measurements to calculate the effects of surface emission on the total emission measured at lower frequencies. These compound measurements should permit us to obtain more sensitive measurements of emission from the interior of the lungs. In particular, we are investigating the use of infrared or millimeter waves to provide surface-temperature data, and a low-frequency microwave radiometer to provide in-depth changes in lung-water content.

The utilization of recent developments in the radiometric techniques such as those involving the independent but simultaneous measurement of the antenna mismatch, and the apparent temperature [12] should certainly help overcome the mismatch problems between the antenna and the human body and hence improve the chances of utilizing our technique clinically. Also, the development of the correlation radiometers [13] should improve the resolution of the lung-water measurements and may lead to the possibility of measuring the distribution of water in the lung.

We note that although the relatively broad antenna viewing angle (beam width) is a crucial problem in the use of radiometry to detect small tumors [6], [7], it is not a crucial problem in the present application because the measurements of even the average change in lung-water content are valuable and of significant importance. Because of the extensive perfusion of the lung region, it is unlikely that the measurements will be limited by localized temperature gradients in the lung. The radiometric technique also does not involve any external radiation and hence it is safe and can be used for continuous monitoring of lung water [3]. We emphasize, too, that the described study is related to the feasibility of using the radiometer to measure only changes in lung-water content, whereby each individual serves as his own reference to establish a base-line signal. Further efforts are still required to investigate the feasibility of using the radiometer for the absolute evaluation of the amount of water in the lung.

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An Empirical Design Technique for Microwave Oscillators

ERIC R. EHLERS, MEMBER, IEEE

***Abstract* — A large-signal design technique for series-type microwave oscillators using three-terminal active devices is described. Using this technique, the characteristics of the embedding circuits required for maximum output power are measured directly under actual oscillation conditions. A "two-signal" technique is used in the measurement to establish the required oscillation conditions and to prevent oscillation at unwanted frequencies. The design technique has been verified by the construction of a 2.7-GHz bipolar transistor oscillator.**

I. Introduction

A variety of techniques have been proposed for the large-signal design of oscillators using three-terminal active devices. One approach is to use large-signal parameters (such as *S*- or *Y*-parameters) or a nonlinear physical model to predict the performance of the active device under actual oscillation conditions. The characteristics of the embedding circuits required for maximum output power at the desired frequency are then calculated [1]–[6]. Another approach uses a two-step procedure [7]–[12]. A one- or two-port circuit that exhibits negative resistance is first designed using small-signal parameters. Estimates of the large-signal performance of the device are often used along with small-signal parameters in the design of this circuit to maximize the available power. This circuit is then characterized under actual oscillation conditions using a large-signal reflection coefficient measurement or a load-pull measurement to determine the circuit terminations that allow maximum power to be delivered to the load.

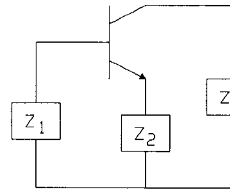

Fig. 1. The basic oscillator topology. One impedance is the output load impedance and two are purely reactive.

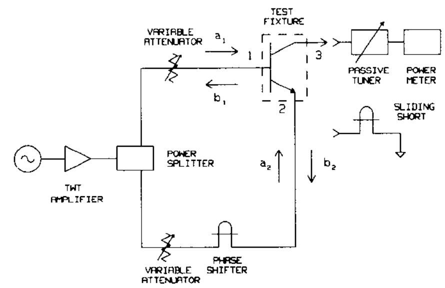

Fig. 2. Simplified test system for establishing oscillation conditions.

Presented in this paper is an alternative design technique for series-type oscillators. The first step in the design is a large-signal measurement that simulates the conditions that would exist during actual oscillation at the desired frequency. In this measurement, the impedances seen by the three terminals of the active device that are required for maximum output power are determined. Circuits are then designed using conventional techniques that present these impedances to the active device.

One advantage of this technique over those described above is that it is a completely large-signal design that does not require a large-signal model. A disadvantage is that the measurement is fairly time consuming and the results are applicable only to the specific conditions established during the measurement. However, for a fixed frequency series-type oscillator, this technique may be preferred since the validity of a nonlinear physical model or large-signal parameters need not be established.

II. Design Technique

The basic oscillator topology is shown in Fig. 1. The embedding circuits for the oscillator consist of three terminating impedances; two are purely reactive and the third is the output load impedance. A simplified test system for simulating oscillation conditions for this topology is shown in Fig. 2. The active device is mounted in a three-port test fixture. One of the ports is terminated with a conventional passive tuner or with a sliding short; the tuner is capable of presenting an arbitrary impedance (within its tuning range) to the device and the sliding short can present an arbitrary reactance. The three-port test fixture, combined with the passive tuner or sliding short, can be thought of as forming a new two-port circuit with characteristics that vary with the impedance established by the tuner or sliding short. The effective impedances presented to the ports of this circuit are established by injecting a signal at the desired frequency into *both* of the ports. Power for the waves incident on the two ports comes from a high power source and power splitter. The amplitude of the two waves are set with the variable attenuators and the relative phase of the two waves is adjustable with a phase shifter.

Manuscript received September 19, 1983; revised January 3, 1984.
The author is with Hewlett-Packard Company, Santa Rosa, CA 95401.