$$\bar{E}=\begin{cases} -\Sigma a_t t r^{t-1}(\cos t\varphi \hat{r}-\sin t\varphi \hat{\varphi}), & |\varphi|<\alpha/2 \\ -\Sigma b_t t r^{t-1}(\cos t(\pi-\varphi)\hat{r}+\sin t(\pi-\varphi)\hat{\varphi}), & |\varphi|>\alpha/2. \end{cases}$$

Applying the boundary condition gives us equations for t and a_t/b_t

$$\epsilon_2 \tan t\alpha/2=-\epsilon_1 \tan t(\pi-\alpha/2)$$

$$\frac{a_t}{b_t}=\frac{\cos t(\pi-\alpha/2)}{\cos t\alpha/2}.$$

The first equation gives us a number of t values. Of these we can only allow positive values since, otherwise, the stored energy will be infinite. We are also only interested in values of t less than 1 for which the fields are singular at the edge, that is

$$0<t<1.$$

This solution is shown in Figs. 1 and 2.

The solution which is odd around the symmetric plane gives an identical dispersion equation if we interchange ϵ_1 and ϵ_2. The equipotential lines in Figs. 1 are equal to the field lines in this case. Here,

$$\frac{a_t}{b_t}=-\frac{\sin t(\pi-\alpha/2)}{\sin t\alpha/2}.$$

The angle factors $\cos t\varphi$ and $\cos t(\pi-\varphi)$ divide the space in different regions with different signs of these factors. The lowest value of t gives two such regions (Fig. 1) while the second gives four regions, and so on. Thus if the field has a reasonably slow angle variation, we must conclude that a large part of it is represented by the lowest t value that is by the singular solution.

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Microwave Apexcardiography

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***Abstract*—A microwave technique for recording apexcardiograms is reported. The technique is based on detecting changes in the reflected microwaves caused by movement of the chest wall in response to left-ventricle activity. Results show that microwave technique is useful for delineating the fine structures in the precordial movement.**

I. Introduction

THE TECHNIQUE of recording the precordial movements is called apexcardiography, and the record is referred to as an apexcardiogram (ACG). The ACG represents the left-ventricular movement caused by low-frequency displacements of the precordium overlying the apex of the heart [1]–[3] and has been correlated with the hemodynamic events within the left ventricle [4], [5]. In all systems used to record ACG, either a displacement (linear) or velocity (gradient) microphone is used to convert the mechanical movement into electrical signals. It is necessary to strap or tape the microphone to the patient's chest. These systems have been found to be unreliable since a tremendous variation in sensitivity results from differing pressures applied to the skin through the microphone. The same problem is manifest even in recent designs using electrooptic sensors [6]. This paper reports the development of a low-power noncontact microwave technique for recording ACG which eliminates any change in sensitivity caused when the sensor is attached to the chest.

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II. Method and Measurement

The principle of operation of the microwave technique is based on detecting the changes in the reflected microwaves caused by the movement of the chest wall in

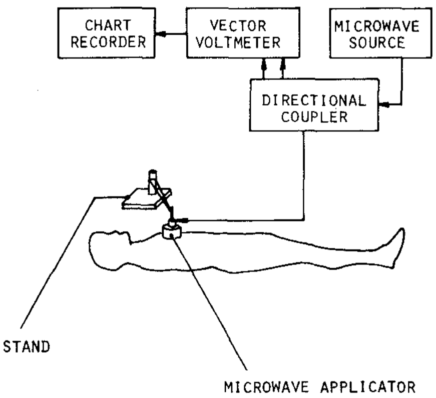

Fig. 1. Schematic diagram for noncontact microwave measurement of precordial movements.

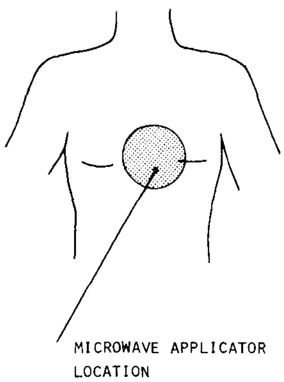

Fig. 2. Position of microwave applicator over the precordium.

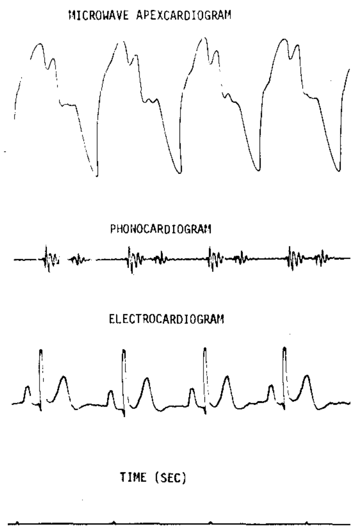

Fig. 3. Microwave apexcardiogram of a healthy young male subject.

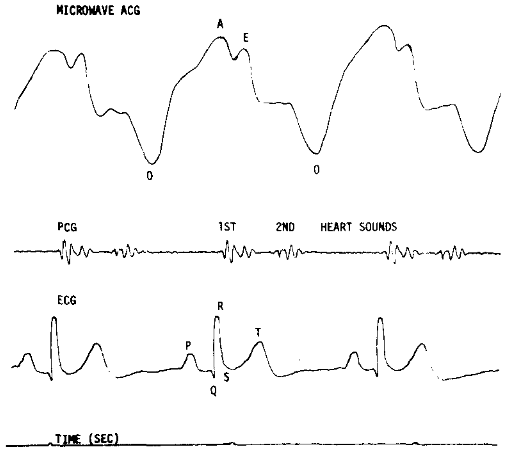

Fig. 4. Relation between microwave apexcardiogram (ACG) and phonocardiogram (PCG) and electrocardiogram (ECG) recorded simultaneously. See text for explanation.

response to ventricular activities. A block diagram of the continuous-wave (CW) microwave system is shown in Fig. 1. Microwave energy is derived from a signal generator (Hewlett–Packard 8614A or Laboratory for Electronics 814A) operating between 2100 and 2500 MHz. The incident power is fed through a 20-dB directional coupler and emitted by way of a coaxial applicator [7]. The reflected microwave signal is modulated both in amplitude and in phase by the moving chest wall. Using the forward signal as a reference, the relative amplitude and phase of the reflected signal are measured as a function of precordial displacement over the apex of the heart, with a vector voltmeter (PRD 2020). The output voltage corresponding to either the amplitude or the phase variation is displayed on a multichannel chart recorder (Grass Model 7).

For the experimental results reported here, the human subject lies in the supine position shown in Fig. 1. The coaxial applicator is located over the apex of the heart with a distance of separation of about 3 cm between the applicator surface and the chest wall (see Fig. 2). It has been found that the amplitude and phase changes depend very much on the applicator location. It is very important that the applicator is placed directly over the apex. Fig. 3 shows the microwave (phase) sensed ACG for a healthy young male who held his breath throughout the measurement. The electrocardiograph (ECG) and phonocardiograph (PCG) tracings for the same subject are recorded simultaneously. The microwave ACG has somewhat different characteristics than a conventional microphone-sensed ACG even though they are all related to the precordial movement. This difference represents the improvement offered by the noncontact microwave technique.

It is seen from the normal apexcardiogram shown in Fig. 4 that toward the end of systole (end of the second heart sound), the mitral valve opens (point 0), and a rapidly rising positive wave occurs due to ventricular filling. Completion of ventricular filling is indicated by the wave (point A) associated with atrial contraction. Point A occurs between the P wave and the QRS complex in the ECG and coincides with the atrial component of the first heart sound. The interval between point A to E represents the period of isometric contraction. The E point marks the beginning of ventricular ejection. It coincides with the first heart sound (the tricuspid components) and follows the QRS complex of the electrocardiogram. A rapid downward deflection which immediately follows the E point represents the period of maximal ventricular ejection. The ACG then reaches a plateau at the level of midsystole, and this is followed by another downward deflection to the point 0 which coincides with the opening of the aortic valve and completes the cycle.

III. Conclusion

A microwave technique for recording ACG is reported. This technique, along with other diagnostic and monitoring applications of microwave energy in medicine [8]–[13], has the unique advantage of not requiring any mechanical contact with the subject. It also has a very wide frequency response limited only by the bandwidth (1 kHz) of the vector voltmeter. It can reproduce, more faithfully than present techniques, the precordial movement of the chest wall caused by left ventricular activities. The technique is simple, uses low power, and is noninvasive.

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