excitation probability contains a factor $\exp(\epsilon/kT)$ where $\epsilon$ is the depth of the (attractive) potential well. In the liquids the neighbors are already near the bottom of the well, and therefore this factor should perhaps be omitted in liquids. Then, the ratio of collision times would be

$$(\tau_{\text{gas}}/\tau_{\text{liq}}) \exp(\epsilon/kT).$$

TABLE II. Factor $\exp(\epsilon/kT)$ at room temperature.

| | $CH_2Cl_2$ | $CHCl_3$ | $CCl_4$ | $C_6H_{14}$ | $C_6H_6$ | $CS_2$ |
|---|---|---|---|---|---|---|
| $\exp(\epsilon/kT)$ | 3.9 | 3.0 | 3.0 | 4.0 | 4.3 | 5.1 |

The resulting factor is shown in Table II. This, however, increases the spread.

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# Ultrasonic Doppler Method for the Inspection of Cardiac Functions

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When the continuous ultrasonic wave is sent forth towards the heart from the surface of the chest wall, the cardiac motion causes the Doppler effect upon the partial wave reflected from it. Therefore, an apparatus suitably constructed for sending and receiving ultrasounds is quite useful for the investigation of the movements of the atrium, ventricle, or valves, etc., through the analysis of the particular Doppler signals developed from the motion of the respective part.

The author developed a method for the inspection of cardiac functions by recording these Doppler signals simultaneously with the electro- and phonocardiographs on the oscillograph paper. This method made it possible not only to obtain direct informations for the valvular movement which could not have been ascertained up to present, but also to examine the transitional aspects of the myocardial excitation which is utterly undetectable by the electrocardiograph alone.

## 1. INTRODUCTION

A PRACTICAL application of the ultrasound to the field of the diagnosis has been developed in the technique employing ultrasonic pulses.[1] Since a slight change in the tissue density of the interior of the body is manifested in the deviation of the transmittivity or the reflectivity of the applied ultrasonic pulses, the pulse technique has been chiefly utilized for the detection of the cancer tissue. Meanwhile, the method under the main title is characterized by the use of the Doppler effect,[2–4] caused by the mechanical motion of the heart, for the inspection of cardiac functions. By means of this method, it is possible to inspect the motion[5] of the heart wall, the movement[6] of the valves, and the heart noises produced in a diseased heart.

This paper proposes to describe the principle and the composition of the equipment in practical use, introducing another way for the clinical examination by discriminating the varieties of the Doppler signals recorded by this original apparatus.

## 2. PRINCIPLE

A sharp beam of an ultrasound being sent forth toward the heart from the surface of the chest wall on the movement of the heart wall or of the valvular structures induces the Doppler effect upon the wave reflected from them. Therefore, if an appropriate probe of sending and receiving the ultrasonic wave is available, it is possible to obtain the AF signals (the Doppler frequencies), frequencies of which are proportional to the motional velocity of the reflecting part of the heart by means of a composite demodulation of the reflected wave with the direct one.

It is obvious that the following relation[7] is established between those quantities designated as $f_d(c/s)$, $u_0$ (cm/sec), and $\lambda$ (cm):

$$f_d = 2u_0/\lambda,$$

where $f_d$ is the Doppler frequency, $u_0$ the velocity component (parallel to the ultrasonic incidence) of the reflecting part, and $\lambda$ the ultrasonic wavelength in the human body. Since the wavelength is determined by

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[1] J. J. Wild and J. M. Reid, J. Acoust. Soc. Am. **25**, 270 (1953); Electronics **28**, No. 3 (1955).

[2] E. J. Barlow, Proc. Inst. Radio Engrs. (1949).

[3] S. Bagno, I. R. E. Convention Record (1954), Pt. 6.

[4] Howry, the ultrasonic blood velocity transducer developed at the National Bureau Standards.

[5] The Doppler signal obtained in a fixed position on the chest wall is a function of the distance of various portions of the heart depending upon the exact rotational and transitional motions that the heart goes through. It is similar to the Kinetocardiogram. E. E. Eddleman *et al.*, Circulation **8** (1953).

[6] Moreover, the Doppler signals by the movement of the valves is the one which is produced by the component of the valvular velocity in the direction of the ultrasound sent forth from the fixed point on the chest wall.

[7] The exact expression is as follows:

$$f_d = \frac{2u_0}{\lambda}\left(1 + \frac{u_0}{c} + \frac{u_0^2}{c^2} + \frac{u_0^3}{c^3} + \cdots\right).$$

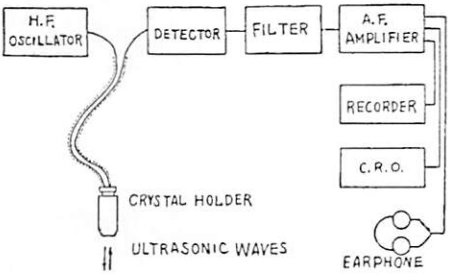

FIG. 1. Schematic block diagram of the apparatus.

the frequency of the ultrasound used, the measurement and the analysis of the frequency of the Doppler signal provides information about the reflecting part of the heart, namely, the ventricles or the valves, etc.

Moreover, the minute vibration[8] of the reflecting part produces the corresponding small alteration in the phase[9] of the reflected wave; a vibratory tone is detected, too.

Employing this method, it is possible to distinguish the Doppler signals produced by the movement of the heart wall or valve, and, further, "the Doppler heart noises" originating at a diseased heart.

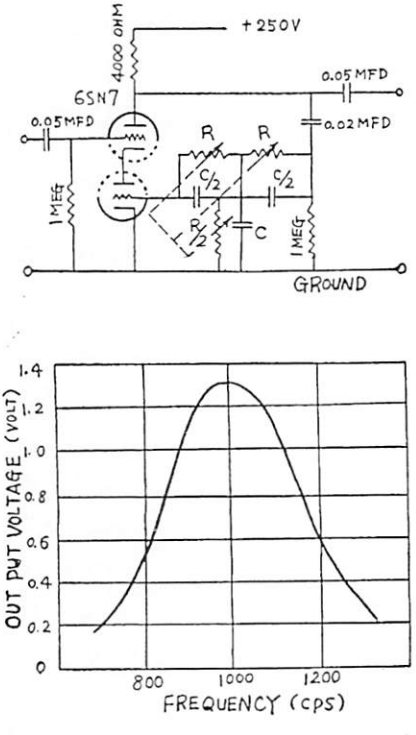

FIG. 2. Circuit and frequency characteristic of the band-pass filter.

### 3. EQUIPMENT

The block diagram of the equipment is presented in Fig. 1. The high-frequency energy supplied by the HF oscillator is conducted to the barium titanate transducer through a flexible cable, and the ultrasound is sent forth into the body. The reflected wave is received by the same transducer, conducted to the demodulator together with a portion of the direct wave. The Doppler signals obtained by the detector are amplified by the AF amplifier, the output power of which drives the earphone or the recorder. The HF oscillator is a typical one of self-oscillation with the power of 1–2 w, and the operating frequency is 3 Mc. The power of the ultrasound is calculated to be about 20–50 mw/cm$^2$. The amplification of the AF amplifier is approximately 80 db.

A low-pass filter and a band-pass filter is added to the AF amplifier. The low-pass filter is of a simple $\pi$ type, the cutoff frequency of which is 500 cps, and the band-pass filter is a twin $T$ circuit,[10] the middle frequency of which is about 1000 cps and a little variable, and the $Q$ is about 3–5. Figure 2 shows the circuit and the frequency characteristic[11] of the band-pass filter.

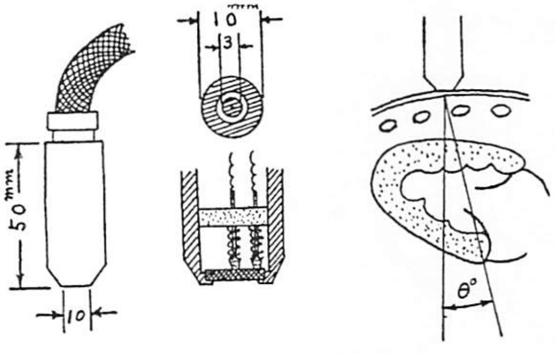

FIG. 3. The shape and the dimensions of the transducer and its holder.

Figure 3 shows the shape and the dimensions of the barium titanate transducer and its holder. The positive electrode is separated in concentric circles, the circular part in the center being operated for the generation of the ultrasound, and the ring-shaped outer part for reception. The schema on the right of Fig. 3 indicates the shape of the ultrasonic beam. $\theta$ shows an angle of the sound intensity reduced to half ($\theta \fallingdotseq 8$ degrees).

### 4. CLINICAL EXPERIMENTS

Practical inspections of the heart are carried out according to the following procedure. The ultrasonic transducer is attached to the surface of the chest wall, searching for the Doppler signals arising from the

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[8] S. Satomura, J. Inst. Elec. Commun. Engrs. Japan 38, No. 4 (1955).

[9] Phase difference $=\frac{4\pi}{\lambda}(r+d)=\frac{4\pi}{\lambda}r+\frac{4\pi}{\lambda}d\approx\Delta\phi+\delta\phi$.

$r$ = range of an object
$d$ = displacement of minute vibration
$\lambda$ = wavelength
$\Delta\phi$ = phase difference corresponding to
$\delta\phi$ = minute change of phase.

[10] $f_0=(1/2\pi CR)$, $f_0$ = middle frequency.

[11] Positive feedback amplifier by means of this filter.

various parts of the heart. The signals thus made audible through the earphone are recorded on the oscillograph paper parallel with the electro- and phonocardiographs.

The above described filters are chosen according to the object under inspection. That is, the low-pass filter is used in case of inspecting the heart wall motion and the band-pass filter is for valves with the middle frequency[12] set at about 1000 cps. In case of receiving the Doppler heart noises, no filter is employed.

Figure 4 shows the particular positions on the chest wall selected for the process of systematic inspections. The Doppler signals thus obtained have been classified into the following three distinct groups:

(a) lower frequency Doppler signals (selected by means of the low-pass filter);
(b) higher frequency Doppler signals (selected by means of the band-pass filter);
(c) Doppler heart noises (no filter employed).

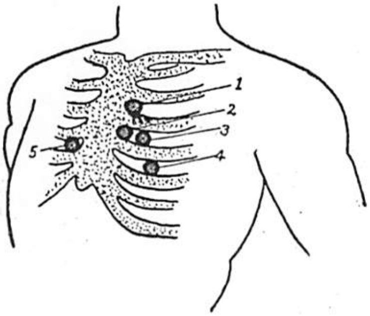

FIG. 4. The particular positions on the chest wall selected for the process of systematic inspections.

### (a) Lower Frequency Doppler Signals

The Doppler signals in this group mainly consist of those arising from the motion[13] of the heart wall, the frequencies being below 500 cps. They are further classified into two classes: those from the ventricular wall and those from the atrial wall according as the ultrasonic probe is placed on the respective position.

The positions for receiving the Doppler signals from the bottom part of the ventricular wall, the apex, and the right atrium are indicated in Fig. 4, (3), (4), and (5), respectively.

In Fig. 5, a representative curve of the Doppler signals is shown, indicating the motion of the bottom part of the ventricle. The curve of the Doppler signals is divided into three components; each one corresponds to the period of the atrial contraction, the ventricular contraction, and the ventricular relaxation, respectively.

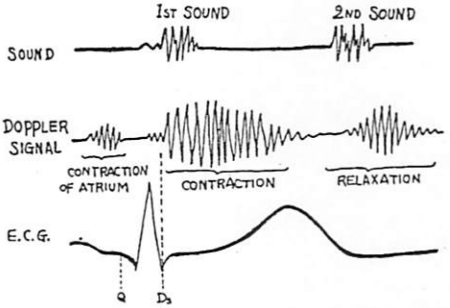

FIG. 5. Schematic graph of the oscillogram, indicating the motion of the bottom part of the ventricle.

A clinical significance is attributed to the investigation of the relations with the time interval between the electromotive excitement of the myocardium and the actual motion of the heart. An abnormal example such as the case with aortic insufficiency has demonstrated the fact that the mechanical motion lags behind the electric excitement of the myocardium at the period of contraction; i.e. as shown in Fig. 5, the time interval $Q-D_s$ between 0.05–0.10 sec for the normal case, whereas for this abnormal case it is about 0.12–0.15 sec.

### (b) Higher Frequency Doppler Signals

Scanning along the left sternal border in the 3rd or the 4th intercostal space or along the parasternal line in the 4th intercostal space as well higher frequencies of approximately 1000 cps can be received coincidently with the lower ones. The higher frequency suggests that the reflecting objects possesses the velocity about 5–10 times larger than that of the ventricle and their location makes it probable that they might be developed by the action of the semilunar or of the atrioventricular valves.

Figure 6 shows the ultrasonic probe directly applied to the exposed heart of an anesthetized dog indicating the positions where the higher frequency Doppler signals are supposed to be produced by the motion of the inner objects.

The position (1) indicates the bottom part of the right ventricle where the tricuspid valve is considered to exist within the position (2) the bottom part of the left ventricle covering the mitral valve and lastly the position (3) represents the bottom of the pulmonary artery the vicinity of the semilunar valve.

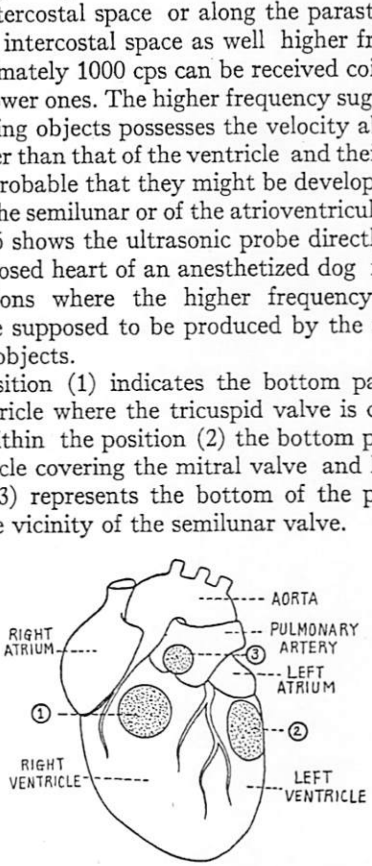

FIG. 6. The positions on the exposed heart of a dog, where the higher frequency Doppler signals are supposed to be produced.

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[12] The middle frequency is so adjusted that the Doppler signal from valves is received with the best intensity.

[13] C. H. Hertz and I. Edler, Acustica 6 (1956).

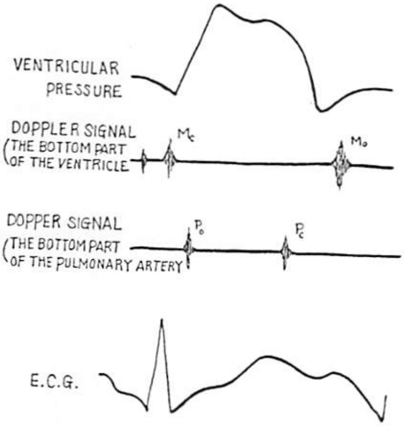

FIG. 7. Schematic graph of the oscillograph, for the experimental results on the heart of a dog.

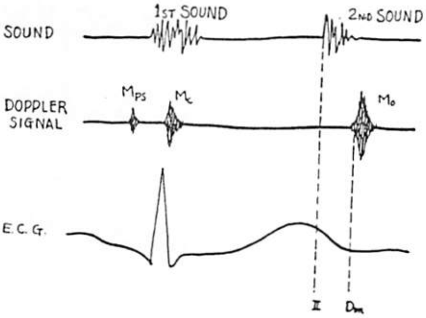

FIG. 8. Schematic graph of the oscillogram, indicating the motion of the mitral valve.

A typical curve of the higher frequency signals recorded on the oscillograph paper is exhibited in Fig. 7 for the experimental results on the heart of a dog. Those taken at the tricuspid position ($M_c$) develop coincidently with the onset of the increase in the pressure curve for the ventricle lagging as much as 0.04–0.05 sec behind the start of *QRS* of the electrocardiograph. $M_c$ shows the signal corresponding to the closing of the mitral valve and $M_0$ to its opening. Those at the position around the pulmonary artery ($P_0$) make appearance approximately in the midst of the increasing portion of the pressure curve lagging about 0.09 sec behind the beginning of *QRS*. $P_c$ shows the signal corresponding to the closing of the pulmonary valve and $P_0$ to its opening.

On the basis of the experimental results described above, these higher frequencies are considered to be produced by the movements of the semilunar or of the atrioventricular valve.

The higher frequencies for a human body recorded along the left sternal border in the 4th intercostal space on the chest wall are presented in Fig. 8, showing the movement of the mitral valve. These are produced both at the opening ($M_0$) and the closing of the valve ($M_{PS}$ and $M_c$). The opening and the closing time of this valve is closely related to the functions of the heart; i.e., the abnormal case with some myocardial change or with some defect at the kidney offers the universal result that the time interval between the 2nd sound and the mitral opening, ($II\ D_m$ in Fig. 8) is prolonged to be 0.19 sec for a most extraordinary case, whereas the normal value lies between 0.05 and 0.07 sec. Besides, the time of occurrence of the signal at the valvular closing, its amplitude, etc., are of high diag-

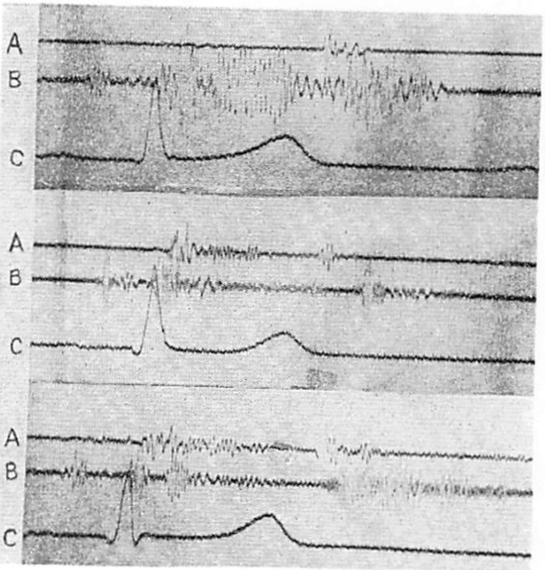

FIG. 9. Oscillograms; the lower frequency Doppler signal, the higher frequency Doppler signal, and the Doppler heart noise, respectively. (*A*—heart sound, *B*—Doppler signal, *C*—E. C. G.)

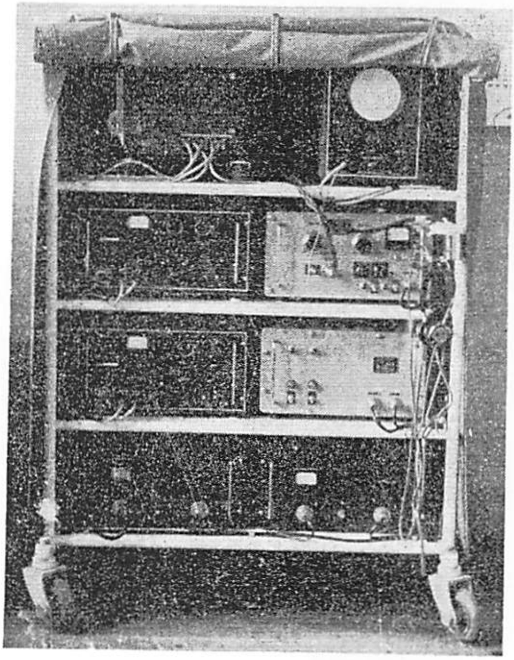

FIG. 10. Photograph of the apparatus.

nóstic significance, providing the possibility for inspecting the condition of the stiffness of the valvular structure. Moreover, the signals by the plumonary artery itself is also detectable on the left sternal border in the 3rd intercostal space.

### (c) Doppler Heart Noises

The Doppler heart noises are obviously audible only on a diseased heart. They are yielded when the reflecting object of the ultrasound, such as the ventricular wall, suffers an irregular vibration of small amplitude. A variety of tones are received according to the species of the objects or to the state of vibrations, etc. Since the amplitude of this cardiac vibration which causes the Doppler heart noises is supposed to be so small as to be less than a quarter-wavelength of the applied ultrasonic wave,[9] the phase of the reflected wave is equivalent to be modulated by the vibration, the demodulation producing a vibratory tone. The important difference from the usual tone heard through a stethoscope is that the Doppler noises cannot be produced unless the ultrasound is applied to the source of the noises or to the vibratory portions. The stethoscope receives the sound considerably diffused from the source. These Doppler noises are also audible, though very weak, to a certain degree from a normal human body, but an abnormal case provides a clearly distinguishable noise, characteristic of the particular defect in the heart. For example, when surplus liquid stays in the pericaudium, the Doppler noises are sure to be audible, even if the stethoscope cannot detect the disorder (see Figs. 9 and 10).

## 5. CONCLUDING REMARKS

The usefulness of the ultrasonic Doppler method for the inspection of the cardiac functions has been described. Incorporating the principle, the equipment diagram, and the experimental examples, an original method for the cardiac diagnosis has been presented. Especially, the detection of the valvular movement is peculiar to this method and new information which other methods could not offer has been obtained. A variety of its application are in prospect for further investigations.

## ACKNOWLEDGMENTS

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# Ultrasonic Pulse Technique for Measuring Acoustic Losses and Velocities of Propagation in Liquids as a Function of Temperature and Hydrostatic Pressure

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A fixed path ultrasonic unit operating in the frequency range of 20–200 mcps is described which can be used for measuring acoustic wave velocities and losses in liquids as a function of temperature and hydrostatic pressure. A simple phase balance technique insures a high order of accuracy for velocity determinations.

Illustrative data for carbon tetrachloride, Dow Corning DC-703 and DC-200 silicone fluids, and water are shown. Determination of freezing points of liquids using ultrasonic waves for indication is also discussed briefly.

## I. INTRODUCTION

OF the very great volume of work that has been done in studying the mechanical properties of liquids with ultrasound, only a relatively small amount has involved the use of hydrostatic pressure as a variable. This is partly due to the fact that means for providing and measuring high pressures are not as readily obtained as for, say, varying temperatures. Also, it is obvious that equipment suitable for use at atmospheric pressure may prove difficult to adapt to the closed system required for application of high pressures. Optical methods, for example, require specially constructed windows in the pressure vessel,[1] while variable path interferometers add the complexity of a shaft which can be rotated from outside the pressure vessel.[2,3]

Particularly for velocity measurements, methods involving fixed path lengths and high-frequency pulse techniques appear to have merit.[4–6]

It is the purpose of this paper to discuss a method which is particularly good for determining velocities of propagation, but one which also yields attenuation. Operation at frequencies as high as 200 mcps appears

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[1] P. Biquard, Compt. rend. 206, 897 (1938).

[2] J. C. Swanson. J. Chem. Phys. 2, 689 (1934).

[3] T. A. Litovitz and E. H. Carnevale, J. Appl. Phys. 26, 816 (1955).

[4] Gerald Holton, J. Appl. Phys. 22, 1407 (1951).

[5] A. H. Smith and A. W. Lawson, J. Chem. Phys. 22, 351 (1954).

[6] J. F. Mifsud and A. W. Nolle, J. Acoust. Soc. Am. 28, 469 (1956).