Intracardiac Phonocardiography

Description of a New Simplified System

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FOLLOWING the pioneering works of Yamakawa et al. (1953)¹ and of Soulié (1954),² Luisada and Liu (1957)³, ⁴ described a method of recording intracardiac sound vibrations utilizing the electric signal of a pressure transducer through differentiation and filtration. At about the same time, Lewis et al. (1957)⁵ used a small barium titanate element at the tip of an intracardiac catheter. More recently Soulié et al. (1959, 1961)⁶, ⁷ published the results of studies with a catheter tip pressure-sound transducer.

The purpose of this paper is to report a new, considerably simplified method of intracardiac phonocardiography, which utilizes the principle of sound transmission along a column of fluid. This method can be utilized both in experimental and clinical studies.

Method

The method that has been developed is basically a “fluid column transmission” method (FCT phonocardiogram), whereby the recording microphone is placed at the proximal end of the catheter.

Several types of microphones were tested. Among them was the Maico contact microphone no. 350-1700-C10. In order to prevent penetration of the flushing solution or blood into the microphone, a thin metal membrane was initially used to separate the fluid from the microphone. These proved unsatisfactory because of damage to the pick-up of the microphones used. The final model was based on the use of a Sonar-type of microphone. This was placed in direct contact with the fluid or blood and gave the best response.

Final Device

The recording of intracardiac or intravascular sound was obtained by connecting the proximal end of a catheter (in addition to the strain gauge for pressure recording) to this newly developed device. The construction consisted of a transparent plastic funnel-shaped housing that contained (a) a funnel with a flat end; (b) a terminal Luer-Lock metal connection for attaching to the catheter at the exit of the funnel; (c) a side Luer-Lock metal connection for flushing the funnel; (d) a flat Sonar-type Hydrophone 2.8 x 2.5 cm in size applied to the mouth of the funnel and kept firmly in place by a plastic ring*; this hydrophone has a free field sensitivity of −91 db for a pressure of 1 microbar within the frequency band of 50 to 500 cps; its capacitance is 5800 μμf; (e) a female plug mounted in the plastic retaining ring providing an electric connection with the hydrophone; and (f) a cable provided of two male jacks, one of which is connected to the female plug of the hydrophone while the other is connected to the input of a no. 1700B Sanborn amplifier with filters for phonocardiography. The apparatus is shown in figure 1.

For experimental recording, the device is filled with physiologic solution (exclusion of air bubbles is essential) and connected to the catheter, which can be introduced into any cardiac chamber or vessel.

For clinical recording, the device is sterilized by filling it with a 0.1-per cent Zephiran solution for 12 hours or more. On the morning of the catheterization, the device is flushed with a 5-per cent solution of dextrose in water and is connected in series to the catheter pressure transducer system either to a side arm of the pressure transducer or of the catheter connections.

The signal is transmitted by the cable connected to the device on one side, and to the phono-

*The authors wish to thank the U. S. Naval Air Development Center of Johnsville, Pennsylvania, and particularly Mr. H. Suter, Supt. Sonar Division, for their courtesy in supplying this type of hydrophone.
cardiographic amplifier on the other. The best filter is selected under oscilloscopic monitoring (RC filters with nominal frequency of 25, 50, 100, 200, or 400 cps are used). The tracing is then recorded simultaneously with any other pressure, electrocardiographic, or external phonocardiographic tracing.

The high-frequency vibrations generated by the heart and large vessels are transmitted along the fluid filling the catheter and funnel to the hydrophone. The latter transduces them into electric pulses which are selected (filter) and recorded (galvanometer).

Results

Animal Experiments

The FCT phonocardiogram was tested in the right ventricle, left ventricle, pulmonary artery, or aorta of 10 normal anesthetized dogs, in the left ventricle of a dog with experimental aortic insufficiency (fig. 2), and in the aorta of a dog with experimental aortic stenosis.

The records obtained with filters having a nominal frequency of 25 cps and 50 cps had several low-frequency vibrations below the sonic range, especially in the case of the 25 cps filter. The records obtained with filters at a nominal frequency of 100, 200, or 400 cps clearly showed the vibrations of the first and second sounds and were free from artifacts or additional vibrations.

The sound tracings recorded from a catheter positioned in the left ventricle in the dog with aortic insufficiency reproduced well the vibrations of the diastolic murmur (fig. 2). A comparison was made between the tracing recorded by the FCT method, that recorded by an AEL phonocatheter, and that recorded by the older method of electronic differentiation (fig. 3). The high-frequency vibrations are poorly recorded by electronic differentiation, are well recorded by the FCT method, and are particularly emphasized by the phonocatheter. On the other hand, medium- and low-frequency vibrations and the heart sounds are well recorded by both the electronic differentiation and by the FCT method, and poorly by the phonocatheter (fig. 3). Therefore, the FCT method seems adequate for recording both high-frequency and low-frequency vibrations. Simultaneously recorded pressure tracings by the FCT phonocardiographic system were free from artifacts in animals with experimental aortic insufficiency (fig. 2) or stenosis, and a comparison of the FCT system and AEL phonocatheter shows that the FCT records the heart sounds better and the high-frequency murmurs with equal fidelity.

Clinical Applications

The FCT phonocardiogram was used during routine diagnostic cardiac catheterization studies in patients ranging in age from 13 months to 30 years with a variety of congenital and acquired cardiac lesions. The use of this method required neither modification nor prolongation of the usual catheterization procedure. Excellent selective intracardiac phonocardiograms were obtained through the nos. 5 and 6 Cournand and TSP catheters used in infants and in children, as well as the larger (nos. 7 and 8) catheters used in adults.

The tracings clearly revealed the vibrations of the murmurs of ventricular septal defect (fig. 4), acyanotic tetralogy of Fallot, mitral stenosis (figs. 5A, 5B, and 6), mitral insufficiency (fig. 5B), and aortic insufficiency (fig.
Figures 2 and 3

**Figure 2**

Tracings from left ventricle in a dog with experimental aortic insufficiency. FCT = i.e. phonocardiogram by means of the new fluid column transmission system. AEL = i.e. phonocardiogram by means of the American Electronic Laboratory phonocatheter. LV press = pressure tracing of left ventricle. Nominal frequency of filters = 400 cps; filter slope = 24 db/octave. Left, film speed 50 mm./sec.; right, film speed 100 mm./sec. The FCT system records better than the AEL the vibrations of the heart sounds and equally well those of the high frequency diastolic murmur.

**Figure 3**

Intracardiac phonocardiograms recorded with various systems from the ascending aorta of a dog with minimal congenital valvular aortic stenosis (autopsy). Ao = aortic pressure tracing. AEL = i.e. phonocardiogram by means of the American Electronic Laboratory phonocatheter. FCT = i.e. phonocardiogram by means of the new fluid column transmission system. Diff = i.e. phonocardiogram by means of the electronic differentiation system from output of strain gauge 25, 50, 100, 200, and 400 cps = nominal frequency of filters; slope = 24 db/octave. The AEL system gives a similar high-frequency response at all filtration levels above 50 cps. The differentiation system gives a poor response at 200 and 400 cps. The FCT system gives a good response from 25 to 400 cps with gradual selective increase of the high-frequency vibrations.
Figure 4

Two-year-old child with ventricular septal defect and a pulmonary flow murmur. Tracings recorded from pulmonary artery through a no. 5 Courand catheter. From above—intravascular phonocardiogram from pulmonary artery (filter at 400 cps with 24 db/octave slope); aortic pressure tracing; electrocardiogram; pulmonary artery pressure tracing. The FCT phonocardiographic system records well the high-frequency systolic murmur in the pulmonary artery.

Figure 5

Tracings recorded in a 27-year-old woman with minimal insufficiency and stenosis of the mitral valve (LAV-LV end-diastolic gradient = 1 mm.). The external phonocardiograms recorded the systolic and diastolic apical and midprecordial murmurs. A, top. From above—intravascular phonocardiogram from wedge position with filter at 50 cps (diastolic-presystolic murmur, opening snap); intracardiac phonocardiogram from left ventricle with filter at 50 cps (opening snap, minimal presystolic murmur). B, bottom. Intracardiac phonocardiogram from left ventricle with filter at 200 cps (two components of first sound, systolic murmur, opening snap, diastolic murmur). LV, left ventricular pressure tracing; W, wedge pressure tracing.

6). Of particular interest were intracardiac phonocardiograms simultaneously recorded from two chambers (fig. 5A).

Discussion

Numerous studies of intracardiac phonocardiography (Feruglio,8 Yamakawa,8 Moscovitz et al.,10) have utilized experimental animals or have been limited to investigation of the right heart. Others (Liu et al.,11 Luisada and Liu,12 Luisada et al.13) dealt specifically with investigations of the left heart and the aorta. Kasparian et al. (1964)14 studied several cases of left heart catheterization by a catheter-tip microphone. Yarza Friarte et al. (1961)15 used a modification of Luisada and Liu's method (a small microphone was ce-
Intracardiac phonocardiography

Figure 6
Tracings recorded in a 47-year-old woman with severe mitral stenosis and moderate mitral and aortic insufficiency. The FCT tracing recorded from within the left ventricle reveals a high-frequency, early-diastolic murmur in decrescendo starting with the opening snap. The vibrations are probably due both to the mitral stenosis and the aortic insufficiency.

In 38 cases with congenital heart disease and in 20 cases of acquired heart disease, Faber and Purvis (1963) also cemented a piezoelectric microphone to the end of a syringe barrel, connected the filled syringe to a catheter, and used it to record intravascular sound.

Since 1956, one of the authors (A.A.L.) has used his original method to obtain automatic simultaneous recording of sound and pressure phenomena during the diagnostic procedure of catheterization. This permitted the operator to draw blood samples and obtain pressure and sound tracings from the catheter while avoiding introduction of additional catheters. Moreover, difficulty in the positioning of phonocatheters (especially in the left heart) and frequent damage of the sensor element are also avoided by this method. These advantages were partially offset by the fact that high-frequency vibrations are poorly recorded, partly because they are above the response limit of the strain gauge, and partly because of damping caused by the catheter.* The results obtained with this method in 172 cases studied by right and left heart catheterization have recently been published (Luisada et al., 1964).13

Cardiac catheterization is primarily performed as a diagnostic procedure; therefore, special care should be taken not to prolong the duration of the test, so that no increased hazard is incurred. Phonocatheters are frequently difficult to introduce in the desired chamber. If introduction is successful, either another catheter is introduced for recording pressures and drawing blood samples (phonocatheter of Lewis, device of Feruglio) or a larger, so-called double-lumen catheter, is employed (Lewis, Soulé). In the latter situation, the larger caliber and physical characteristics (rigidity) of the catheter render catheterization more difficult and often unsuccessful, especially in infants and children or in the case of left heart catheterization.

Sound vibrations travel in water with a speed of 1,500 M./sec; thus the rapid intracardiac vibrations reach the pickup with a delay of 0.5 to 0.7 millisecond. A further delay is introduced by the filters, so that an actual delay of 2 to 5 millisecond, can be observed in the tracings in comparison with external phonocardiograms or with intracardiac phonocardiograms recorded by means of a phonocatheter. Actually this delay is not visible unless the film strip is recorded with a speed of 100 or 200 mm./sec. While this minimal delay may be considered a disadvantage in the comparison with external phonocardiograms, it should be kept in mind that it represents an advantage whenever one compares the intracardiac sound tracing with the intracardiac

*An objection was voiced in the past, namely, that the high-frequency vibrations derived from the signal of the pressure transducer were different phenomena from the heart sounds and murmurs. This objection has gradually lost its validity because recent studies (Faber and Purvis, Piemme and Dexter, Dexter) have revealed that the main vibrations of the heart sounds coincide in time with the rapid rises and drops of the pressure tracings, confirming that they can be derived from the latter through differentiation.

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pressure tracing because both tracings suffer from the same delay.

The current FCT phonocardiographic modification of the original method of Luisada and Liu has the advantage that it increases the high-frequency response of the system without decreasing the response to the medium-low frequency vibrations, so that both are recorded with fidelity.

The avoidance of the need for additional catheters, the automatic simultaneous recording of intravascular and intracardiac pressure tracings and sound through a single lumen, and the ease with which both medium-low and medium-high frequency vibrations are recorded are great advantages in comparison with other existing systems.

The demonstration of the feasibility and ease of application of the FCT phonocardiographic system in routine cardiac catheterization indicates that a significant increase in the utilization of intracardiac phonocardiography as a practical diagnostic tool is now possible. Since all the cardiac chambers are now easily accessible to catheter exploration but the pressure tracings sometimes do not demonstrate evidence of the lesions suggested by clinical auscultation, the complementary nature of the new technic should prove extremely useful.

Summary

A new system for recording intracardiac and intravascular sound during routine catheterization is described.

This system is based on the application of a flat, sonar-type, barium titanate microphone at the end of the catheter, so that the vibrations of the blood within the chambers of the heart and vessels are transmitted along the fluid in the catheter, and transduced by the microphone (fluid column transmitted phonocardiogram–FCT phonocardiogram).

Comparative studies between the response of the FCT system and other systems for intracardiac phonocardiography are made in normal dogs and in dogs with experimental aortic lesions. It is demonstrated that the FCT system gives a good response for vibrations between 25 and 400 cycles per second.

Representative phonocardiographic tracings in patients with congenital or acquired heart disease during routine cardiac catheterization are presented.

References

INTRACARDIAC PHONOCARDIOGRAPHY


**Earliest Measurement of Peripheral Vascular Resistance**

Hales' studies on peripheral resistance carried out on the dog concerned the perfusion of water at body temperature through the descending aorta. The volume of flow was measured as the perfusing fluid escaped through a cut in the intestine. Continuing the experiment, he followed the mesenteric vessels and severed them, progressing toward the aorta. The resistance was maximum the furthest removed from the large vessel. Also he observed that the combined cross section of the branches beyond a bifurcation was greater than the cross section of the parent trunk central to the branching.

"I Slit open with a Pair of Scissors, from end to end, the Guts of a Dog, on that side which was opposite to the Insertion of the mesenterick Arteries and Veins; and having fixed a Tube 4½ Feet high to the descending Aorta a little below the Heart, I poured blood warm Water thro' a Funnel into the Tube, which descended thence into the Aorta, with a Force equal to that, with which the Blood is there impelled by the Heart: This Water passed off thro' the Orifices of innumerable small capillary Vessels, which were cut asunder thro' the whole Length of the slit Gut. But notwithstanding it was impelled with a Force equal to that of the arterial Blood in a live Dog, yet it did not spout out in little distinct Streams, but only seemed to ouze out at the very fine Orifices of the Arteries, in the same manner as the Blood does from the capillary Arteries of a muscle cut transversely.

"But the Resistance which the Blood meets with in those capillary Passages, may be greatly varied, either by the different Degrees of the Viscidity or Fluidity of the Blood, or by the several Degrees of Constriction or Relaxation of those fine Vessels.

"And as the State of the Blood or Blood-vessels are in these Respects continually varying from divers Causes, as Motion, Rest, Food, Evacuations, Heat, Cold, &c. so as probably never to be exactly the same, any two Minutes, during the whole Life of an Animal, so nature has wisely provided, that a considerable Variation in these, shall not greatly disturb the healthy State of the Animal."

Variations in peripheral vascular resistance were measured by observing the effect of heat and brandy. . .

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