Intracardiac Phonocardiography
Correlation of Mechanical, Acoustic and Electric Events of the Cardiac Cycle

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Attempts to record heart sounds and murmurs at their site of origin are not new. For obvious reasons, sounds picked up from the surface of the thorax are not a true representation of the actual vibrations of the cardiac valves and walls. Thus, physiologists have attempted to move their recording instrument closer to the sound source by placing microphones in the esophagus, \textsuperscript{1,2} by suturing microphones to the myocardium in experimental animals, \textsuperscript{3} by applying suction microphones directly to the surface of the human heart, \textsuperscript{4} and finally by introducing the microphone into the interior of the cardiac chambers themselves. Intracardiac microphones have been described by Yamakawa, \textsuperscript{5} Soulié, \textsuperscript{6} Lewis, \textsuperscript{7} and by Luisada. \textsuperscript{8} We have used a ceramic microphone sealed in the tip of a standard double-lumen cardiac catheter to correlate the mechanical and acoustic events of the cardiac cycle in animals with experimental valvular lesions and arrhythmias and in patients with heart disease.

Methods and Materials

The microphone consists of a modified barium titanate element called Glennite, \textsuperscript{9} which is endowed with piezoelectric properties by special polarizing treatment. The ceramic element of the microphone, 1.2 mm in diameter and 15 mm in length, is fixed at one end of the catheter shell to form a cantilever (fig. 1). As the sensitive diaphragm vibrates in accordance with the sound, a rigid pointer transmits the mechanical motion to the ceramic. Because of its piezoelectric property, the ceramic on bending generates a voltage which is transmitted along the electric leads to the external circuit amplifiers and oscillographic recorder. The response is flat between 20 and 3,000 c.p.s.

Results

Normal Heart Sounds. With the microphone located in the dog’s left atrium, 4 distinct sounds can be detected (fig. 2). More precise identification of heart sounds can be achieved by recording them simultaneously with multiple pressure pulses.

In an open-chest dog, it is possible to record synchronously pressure tracings from the left atrium, ventricle and aorta, together with an intracardiac phonocardiogram and an electrocardiogram (fig. 3). Since an intracardiac microphone records sounds from one side of the heart with minimal interference from valve areas on the opposite side, analysis of the individual heart sounds is considerably simpler. The first component of the first sound appears to be synchronous with atrioventricular pressure curve crossing (apparently the time of mitral valve closure); the second component of the first sound occurs at

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Cross-sectional diagram of intracardiac microphone. The ceramic element is 1.2 mm. in diameter and 15 mm. in length.}
\end{figure}
the time of aortic valve opening. The second heart sound appears at or immediately before the incisura. The third sound, when recorded, occurs on the downstroke of the V wave. From such a tracing one can see that the interval between the 2 components of the first sound equals isometric contraction. The interval between the second component of the first heart sound and the second heart sound is total ejection. Total systole is bounded by

FIG. 3. Correlation of intra-aortic heart sounds in a dog with mechanical events of the cardiac cycle of the left heart.

FIG. 4. Relationship between mechanical and acoustic events of the cardiac cycle.

the first component of the first heart sound and the second sound. Total diastole is equal to the time elapsed between the second sound and the initial vibrations of the first heart sound.

It is conceivable then that one could determine the duration of the phases of the cardiac cycle with a good deal of precision, from a well-written phonocardiogram. In figure 4, the length of the individual phases as measured from the pressure curves is plotted on the horizontal axis, and their duration determined from the intracardiac phonocardiogram on the vertical axis. Good correlation exists for total diastole, systole and ejection, only fair correlation for isometric contraction. If, however, one would be satisfied to obtain the duration of isometric contraction from the phonocardiogram with a permissible error of ± 0.02 second, the correlation would be quite good, all points but 1 falling within this area.

Premature Ventricular Contractions. After a frustrate premature contraction, blood is ejected from the ventricle during the next beat with an increase in volume and velocity of flow. This is often sufficiently great to exceed the critical Reynolds number, result in turbulent flow, and give rise to a murmur detectable when the microphone is in one of the
great vessels (fig. 5 Top). This can also be seen on the right side of the heart during a short run of bigeminal rhythm (fig. 5 Bottom). Flow murmurs are detectable in the pulmonary artery when blood is ejected from the over-filled ventricle during the regular sinus beats.

Aortic and Pulmonic Stenosis. A constricting suture about the aortic root in a dog gives rise to aortic stenosis. The diamond-shaped murmur of aortic stenosis is generated at the stenotic area and does not depend upon transmission through the chest wall for its characteristic configuration (fig. 6 Top). The maxi-
The intensity of the murmur occurs after the anacrotic notch suggesting that the greatest flow occurs after this point. In simulated pulmonic stenosis, a diamond-shaped murmur is produced whose intensity is modified by the interrelationship of orifice area, magnitude of flow and velocity of discharge. It can be seen that the murmur is louder with moderate stenosis than during such severe degrees of stenosis that flow through the valve is markedly restricted (fig. 6 Bottom).

Mitral Stenosis. The presystolic rumble of mitral stenosis at times is difficult to record with some types of phonocardiographic equipment. In figure 7 experimental mitral stenosis is produced by a constricting suture encircling the mitral annulus. Note the atrial sound in the first beat before the suture about the mitral annulus is tightened and the loud presystolic murmur which develops as the left atrial pressure rises.

Aortic Insufficiency and Stenosis. Of considerable interest was the fact that the murmur of aortic insufficiency shown in the first
**Fig. 7** Top. Mitral stenosis in a dog. The presystolic murmur is detected by the microphone located in the left atrium and increases in intensity as the left atrioventricular pressure gradient rises.

**Fig. 8** Middle. Superimposition of aortic stenosis on a dog with aortic insufficiency. The microphone in the aorta initially records a long diastolic murmur during uncomplicated aortic regurgitation. As stenosis is superimposed, not only does a systolic murmur appear, but the diastolic murmur becomes more intense.

**Fig. 9** Bottom. Right ventricular sounds in a patient with constrictive pericarditis. The early diastolic sound(s) is more easily identified inside the ventricle than by the conventional chest wall phonocardiogram (phono.).
2 beats of figure 8 becomes louder with the superimposition of aortic stenosis. This apparently was due to an increase in turbulence as a well maintained regurgitant flow traversed the narrowed aortic orifice.

Constrictive Pericarditis in Man. The early diastolic sound of constrictive pericarditis which is an extremely valuable diagnostic sign occurs at the lowest point on the ventricular curve (fig. 9). It apparently occurs at the time the rapidly filling ventricle abruptly meets the restrictive pericardial envelope and can fill no further without the cost of a marked rise in diastolic pressure.

The versatility of this instrument recommends it for further investigative work in basic hemodynamic problems and as an aid in clinical diagnosis. We visualize that some day, not far off, the cardiac physiologist will be armed with a multipurpose cardiac catheter. This single instrument will not only be capable of obtaining pressures and blood samples for oxygen analysis. It will also permit injection of radiopaque dye directly into any of the cardiac chambers for the more precise delineation of the interior anatomy of the heart. Finally, it will be capable of more accurately localizing cardiac defects by detecting murmurs at their source.

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