Use of the Ultrasonic Doppler Method for Timing of Valvular Movement
Application in the Differential Diagnosis of Extra Heart Sounds

By John B. Kostis, M.D., Dietrich Fleischmann, M.D., and Samuel B. Bellet, M.D.

SUMMARY
The ultrasonic Doppler method was employed to time the rapid movements (opening and closure) of the mitral and aortic valves. To exclude signals due to slowly moving structures (heart walls), the Doppler tracing was processed by a filter that eliminated low frequencies. Clear tracings containing two deflections, one due to the opening and the other to the closure of each valve, were obtained. The valvular origin of the deflections was verified by recordings simultaneous with intracardiac pressures in five dogs.

The ultrasonic Doppler tracing was found to be a satisfactory aid in the differentiation of various extra heart sounds in 24 patients. Thus, the second heart sound precedes, the third heart sound follows, and the opening snap is simultaneous with the signal due to mitral opening. The fourth heart sound is simultaneous with the atrial component of the unfiltered Doppler signal. Ejection clicks and systolic clicks are simultaneous with or follow the signal due to aortic opening.

Because of its simplicity and safety, this method used in conjunction with the phonocardiogram should prove helpful in distinguishing the opening snap, third and fourth heart sounds, and certain additional auscultatory phenomena.

Additional Indexing Words:
Phonocardiography Ultrasound

The identification and differentiation of extra heart sounds is important for adequate evaluation of patients with heart disease. Although the phonocardiogram and electrocardiogram are usually sufficient for timing, additional methods are often necessary to correlate them with specific hemodynamic events. Thus, it is sometimes difficult to differentiate a widely split second sound, an opening snap, and a third heart sound on the basis of their delay after the aortic second sound alone. In other cases the distinction between atrial and ventricular gallop is difficult. The carotid pulse tracing, the apexcardiogram and the jugular venous pulse tracing, which have been used, are indirect methods and in certain instances are insufficient for this purpose. Since the opening and closure of the cardiac valves are of great significance in the evaluation of the time relationship of the events of the cardiac cycle, an ultrasonic Doppler technic was used for the detection of the rapid movements of the mitral and aortic valves. By correlating the ultrasonic Doppler tracing thus obtained with a simultaneous phonocardiogram, definite information relative to the nature of the additional sound may be obtained.

The purpose of this report is to describe our studies depicting the relationship of the ultrasonic deflections to valvular opening and
closures as determined by the intracardiac pressure curves, and our experience in the use of this technic, slightly modified, in the differentiation of additional heart sounds.

Principles and Methods

The principles of the ultrasonic Doppler method and the apparatus used have been described in detail elsewhere. The method is based on the Doppler effect, that is, the apparent change in the frequency of sound when the sound source or the observer, or both, move with respect to each other.

Thus, when ultrasound emitted from a source on the chest wall is reflected on the moving heart, it undergoes a change in frequency ("Doppler shift"). The Doppler signal which is obtained has a frequency proportional to the velocity of the reflecting structure. As the heart contains many structures moving with different velocities, the Doppler tracing is a composite of many signals of different frequencies. To obtain signals due to the rapid movements of the valves only, the signal is processed by a filter favoring high frequencies (corresponding to the velocities of opening and closure of the valves) and excluding low frequencies which are due to the slow movements of the valves and the heart wall. This filter is a cascade of a high pass filter with cutoff frequency of 800 cps and a band pass filter tuned to 1,250 cps with a Q 3.1.∗

High frequency signals due to blood flow which are obtained when the direction of the ultrasonic beam is parallel to the direction of blood flow are continuous and have a "hissing" quality. They can be easily differentiated from the short snapping valvular signals by means of an audiophone or by inspection of the tracing.†

The high frequency Doppler signals obtained in this manner were processed by the "Doptone velocity-amplitude converter"† which instantaneously yields two DC signals: one proportional to the amplitude and the other proportional to the frequency of the Doppler beat. The latter was used for timing of the rapid movements of the valves. The peak of the deflections (corresponding roughly to the time of the maximum velocity of the valve) was used for measurements. The deflections thus obtained are more distinct and can be more easily analyzed than those previously reported. Signals due to the mitral valve movement were obtained by placing the transducer on the fourth left intercostal space about 2 to 3 cm from the sternal border. Aortic valve signals were obtained from the third left intercostal space about 2 cm from the sternal border. The direction of the transducer was slowly changed until satisfactory signals were obtained and continuous signals due to blood flow were eliminated.

The envelope (contour) of the unfiltered Doppler signal obtained with the transducer at the fifth right intercostal space near the sternum was used for timing of the fourth heart sound. The presystolic component (a) of this tracing corresponds to the atrial contraction. Ten normal subjects and 25 patients with extra heart sounds were studied. In the patients with heart disease, the clinical diagnosis was proven by cardiac catheterization. The electrocardiogram, phonocardiogram, and the high frequency Doppler tracing were recorded simultaneously employing an 8-channel photographic recorder. Paper speed of 100 mm/sec and time lines every 40 msec were used.

To verify the significance of the deflections, the high frequency Doppler tracing was recorded simultaneously with intracardiac pressures in five dogs under pentobarbital anesthesia (25 mg/kg). The left ventricle, left atrium, and aorta were catheterized in a retrograde manner utilizing the femoral and carotid arteries which were exposed via surgical cutdown. Identical no. 7 NIH, 100-cm long, catheters and P23Bd Statham transducers were employed. The delay of the transmission of a pressure pulse through the recording system is in the order of 10 msec. As the delay in the transmission of ultrasound in the tissue is negligible (velocity = 1,500 m/sec), 10

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∗When 2.25 mc ultrasound is used, the target velocity corresponding to Doppler frequencies of 1250 cps and 800 cps is 41.7 cm/sec and 26.7 cm/sec, respectively.

From the formula: 

\[ f_d = f_o \frac{2V}{C} \]

Therefore 

\[ V = \frac{f_d \cdot C}{2f_o} \]

where 

\[ f_d \] is frequency of Doppler beat

\[ f_o \] is frequency of emitted ultrasound (2.25 mc)

\[ V \] is target velocity

\[ C \] is velocity of ultrasound in tissue


‡Electronics for Medicine, White Plains, New York.
msec were subtracted from the timing of all pressure measurements.

Results

Doppler Signals Due to Rapid Valve Motion

Signals due to the rapid movements of the mitral and aortic valves were obtained. They are composed of two deflections, one corresponding to the opening, and the other to the closure of the valve. The signal due to mitral valve closure (MC) occurs 0.03 to 0.08 sec after the Q wave and coincides with the major component of the first heart sound. The signal due to the opening of the mitral valve (MO) occurs 0.05 to 0.10 sec after the aortic component of the second heart sound (or the signal due to aortic closure) and near the end of the T wave (fig. 1B).

The signal due to the aortic opening (AO) occurs 0.08 to 0.14 sec after the Q wave or 0.04 to 0.08 sec after the signal due to the mitral closure. The signal due to the aortic closure (AC) is simultaneous with the aortic component of the second heart sound and the T wave (fig. 1A).

Hemodynamic Studies (Fig. 2)

The onset of the signal due to mitral closure is simultaneous with the crossing of the upstroke of the left ventricular pressure with left atrial pressure curves at the beginning of systole. It precedes the corresponding point of the right-sided pressures. The onset of the signal due to mitral opening coincides with the point where the left atrial pressure curve crosses the dicrotic notch of the left ventricular pressure curve and follows the corresponding point of the right-sided pressure waves (fig. 2B).

The beginning of the signals due to the aortic opening is simultaneous with the beginning of the upstroke of the aortic pressure curve, that is, the point where it is crossed by the ventricular pressure curve and follows the corresponding point of the right-sided pressure curve. The onset of the signals due to aortic closure coincides with the dicrotic notch of the aortic pressure tracing, that is, the time when the ventricular pressure falls below the aortic (fig. 2A). It precedes the dicrotic notch of the pulmonary artery pressure curve. Thus, the deflections of the Doppler tracing are simultaneous with the

Figure 1

Signals due to the aortic (A) and mitral (B) valves in a 20-year-old male with mild mitral regurgitation. (Upper tracing) ECG, lead II. (Lower tracing) High frequency Doppler tracing. (Middle tracing) Phonocardiogram at the apex.

Note that the signal of the aortic opening (AO) occurs after the first heart sound (S1); the aortic closure (AC) is simultaneous with the second heart sound (S2); the mitral closure (MC) is simultaneous with the first heart sound; and the mitral opening (MO) follows the second heart sound (see text). Time lines every 40 msec.
Simultaneous recordings of the electrocardiogram (EKG), phonocardiogram (PCG), high frequency Doppler tracing (DT), and intracardiac pressures (AO = aorta, LV = left ventricle, RV = right ventricle, LA = left atrium) in the dog.

(A) Signals due to the rapid movements of the aortic valve. Aortic opening (AO) and aortic closure (AC) coincide with the crossing of the left ventricular and aortic pressure curves at the beginning and the end of systole. AC is simultaneous with the dicrotic notch of the aortic pressure tracing. Time lines every 40 msec (see text).

(B) Doppler signals due to the rapid movements of the mitral valve. The signals due to mitral closure (MC) and mitral opening (MO) correspond to the crossing of the left ventricular and left atrial pressures in systole and diastole. MC is simultaneous with the first heart sound.
opening and closure of the cardiac valves as determined from the crossings of the intracardiac pressure curves.

Use of the Doppler Tracing in Phonocardiography

Timing of Early Diastolic Events

Eighteen patients with an opening snap, third heart sounds, or widely split second heart sound were studied (table 1). In seven patients with mitral stenosis the opening snap occurred simultaneously with the Doppler signal due to the opening of the mitral valve (fig. 3). The third heart sound associated with mitral regurgitation, left ventricular failure, or the physiologic S3 followed the signal due to mitral opening (fig. 4). In three cases with a widely split second heart sound the pulmonic component preceded the signal due to mitral opening (fig. 5B).

Timing of Presystolic and Systolic Events

The aortic ejection click observed in two cases was simultaneous with the signal due to aortic opening and followed the signal due to mitral closure by 0.04 to 0.08 sec (fig. 6). The first heart sound was simultaneous with the signal due to mitral closure (figs. 1 to 6). The fourth heart sound occurred before mitral closure, and it was simultaneous with the presystolic component of the unfiltered Doppler signal with the transducer placed at the fifth right intercostal space near the sternum (fig. 7). This signal corresponds to atrial contraction.11, 12

Differentiation of the Aortic Second Sound from the Pulmonic Second Sound

In all patients studied we were able to obtain the signal due to the closure of the aortic valve. Signals due to the pulmonic valve were not consistently recorded. For the detection of signals due to the pulmonic valves, the transducer was placed one intercostal space higher than the corresponding site for the aortic valve recordings.6, 10

In cases with wide but normal splitting of the second sound, the Doppler signal due to aortic closure coincided with the first component of the second heart sound (fig. 5A), while in cases with left bundle-branch block with paradoxical splitting it coincided with the second component of the second heart sound (fig. 8A). Further identification of the components of the second heart sound was obtained by the carotid tracing and by observing the effect of inspiration on the phonocardiogram and the Doppler tracing.

Discussion

The ultrasonic Doppler method was first introduced in cardiology by Satomura,5 and applied by Yoshida, Nimura and their associates,6-10 for the detection of rapid valve movements in the analysis of the cardiac cycle in normal subjects and patients with left ventricular overloading, mitral valve disease, hypertension, and other clinical disorders. Verification of the valvular origin of the signals was obtained by utilizing the site of application and direction of the transducer on the exposed dog heart, the phonocardiogram, and from simultaneous recordings of the Doppler tracing with the ultrasonic echogram from the same target.

Table 1

Auscultatory Findings and Clinical Diagnosis

<table>
<thead>
<tr>
<th>Auscultatory finding</th>
<th>Clinical diagnosis</th>
<th>No. of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal S1 and S2</td>
<td>Normal condition</td>
<td>10</td>
</tr>
<tr>
<td>Third heart sound</td>
<td>Physiologic (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left ventricular failure (3)</td>
<td></td>
</tr>
<tr>
<td>Fourth heart sound</td>
<td>Mitral regurgitation (2)</td>
<td>7</td>
</tr>
<tr>
<td>Opening snap</td>
<td>Mitral stenosis</td>
<td>3</td>
</tr>
<tr>
<td>Widely split second sound</td>
<td>RBBB pattern, ASD</td>
<td>4</td>
</tr>
<tr>
<td>Paradoxically split second sound</td>
<td>LBBB</td>
<td>1</td>
</tr>
<tr>
<td>Aortic ejection click</td>
<td>Hypertension, dilated aorta</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>34</td>
</tr>
</tbody>
</table>
Simultaneous recordings of the Doppler tracing and the intracardiac pressure curves in the dog reported here further support the opinion that these signals are due to the rapid movements of the valves. The signals due to the opening and closure of the mitral valve coincided with the points of intersection of left atrial and left ventricular pressure tracings, while the aortic valvular signals were simultaneous with the crossing points of the left ventricular and aortic pressures. These crossing points correspond to the rapid movements of the cardiac valves. The time of the rapid movements (opening and closure) of the cardiac valves is important in the study of the dynamic events of the cardiac cycle. The closure of the aortic and mitral valves can be determined from the phonocardiogram. Information relative to the opening of these valves can be obtained from the

Figure 3

Opening snap in a 53-year-old male with rheumatic mitral stenosis of moderate degree and mild mitral regurgitation. Note that the opening snap (OS) coincides with the Doppler signal due to mitral opening (MO). Time lines every 40 msec.
ULTRASONIC DOPPLER METHOD

Figure 4

Ventricular gallop in a 40-year-old male with cardiomyopathy. Note that the gallop sound ($S_3$) follows the Doppler signal due to mitral opening (MO). Time lines every 40 msec. Compare with figure 3.

carotid pulse tracing and the apexcardiogram. However, these methods are indirect and have certain disadvantages. With the ultrasonic Doppler technic the time of rapid movement (opening and closure) of the mitral and aortic valves can be ascertained more directly and without delay because of the great velocity of ultrasound in tissue (1,500 m/sec). Information obtained by this method can be used for the timing and differentiation of the various phonocardiographic transients. The Doppler signal due to mitral opening is simultaneous with the opening of the mitral valve and thus it can be employed for the differentiation of the opening snap which is simultaneous with it from the third heart sound which follows it and from the second component of a widely split second heart sound which precedes it. The validity of this procedure was proven by its utilization in cases in which the clinical diagnosis was verified by cardiac catheterization. Differentiation of these early diastolic sounds on the basis of the $S_2$-$S_3$ interval alone is not always possible.

The signal due to aortic opening may be used for the differentiation of the first heart sound which precedes it from the ejection clicks and systolic clicks which occur simultaneously with it or follow it. Distinction between a normal and a paradoxical splitting of
the second heart sound may be made by the use of the Doppler signal due to aortic closure which is simultaneous with the aortic component of the second heart sound.

Fourth heart sounds and atrial gallops are simultaneous with the atrial component of the unfiltered Doppler tracing which depicts movements of the atria.11, 12

Because of the simplicity of application, this method is useful in the study of certain auscultatory phenomena and promises to become a useful adjunct to the methods employed in phonocardiography.

Acknowledgment

We wish to thank Dr. Dennis Abelson of the University of Pennsylvania for his helpful suggestions regarding the use of the Doppler technic in the study of the cardiovascular system.

Figure 5

Wide splitting of the second heart sound in a 65-year-old diabetic female with complete A-V heart block and right bundle-branch block. (A) The first component of the second heart sound (A2) coincides with the Doppler signal due to aortic closure (AC). Time lines every 40 msec. (B) P2 precedes the signal due to mitral opening (MO). Compare with figures 3 and 4.

References

Figure 6

Ejection click in a patient with hypertension. The ejection click (EC) coincides with the signal due to aortic opening (AO). Time lines every 40 msec.
Figure 7

Fourth heart sound in a female, 23 years of age, with mild mitral stenosis. The fourth heart sound coincides with the presystolic component, "a," of the unfiltered Doppler signal (see text). Time lines every 40 msec.
Figure 8

Paradoxical splitting of the second sound in a 50-year-old male with atherosclerotic heart disease and left bundle-branch block.

(A) Expiration: Note that the signal due to aortic closure (AC) corresponds to the second component ($A_2$) of the second sound. (B) Inspiration: Note that $P_2$ and $A_2$ coincide (forming $S_2$).


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