Echophonocardiographic Studies of the Contribution of the Atrioventricular Valves to the First Heart Sound

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SUMMARY The movements of the mitral, tricuspid and aortic valves have been recorded echocardiographically and related to the first heart sound (S₁) in patients with various hemodynamic and conduction abnormalities. Closure of the mitral and tricuspid valves has been studied with respect to the corresponding atrioventricular pressure crossovers and it is clear that both valves finish closing about 50 msec after pressure crossover. In order to clarify the relative contribution of tricuspid valve closure and aortic root events to the second high frequency component of S₁, a new simultaneous dual echophonocardiographic technique was employed. This permitted the simultaneous registration of tricuspid and aortic valve movements and demonstrated that in certain circumstances the second high frequency component of S₁ could be attributed to tricuspid closure, aortic root events being excluded from the genesis of this sound.

While evidence has accumulated that the first high frequency component of S₁ is related to echocardiographically determined mitral valve closure, differences of opinion persist concerning the contribution of tricuspid valve closure to the second high frequency component of S₁. These are in part explained by the close temporal relationship of tricuspid valve closure and the onset of the ejection of blood into the aorta.

The present study addresses itself to presenting further evidence for a unified theory of the importance of atrioventricular valve closure in the genesis of both high frequency components of S₁. Specifically we have studied: 1) the relationship between right and left atrioventricular pressure crossovers and the closure of the tricuspid and mitral valves, 2) the second high frequency component of S₁ in patients in whom tricuspid valve closure and aortic valve opening can be clearly separated in time because of a hemodynamic or conduction abnormality. To assist further in determining which of two closely related valvaral events might be responsible for the genesis of one particular heart sound, we have developed a new technique in which the phonocardiogram is recorded simultaneously with echocardiographic signals from two different cardiac structures.

Materials and Methods

A total of 14 patients were selected for special study following the registration of a standard echophonocardiogram, recorded on a Cambridge Multichannel Physiologic Recorder as previously described.

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High Speed Echophonocardiography

When valve movements were recorded at 200 mm/sec on an Irex Multichannel Recorder, the echocardiograms were appropriately magnified to compensate for the increased recording speed. In each case the identity of the particular valve under study was determined by conventional echocardiography prior to magnification. Closure of the atrioventricular valves was assumed to occur at the point where the anterior and posterior valve cusps meet (C point). In some cases it was not possible to record two of the leaflets of the tricuspid valve and in these instances, the point of sudden halting of the closing movement of the visualized cusp was taken as valve closure.

Simultaneous Dual Echocardiography

In nine patients simultaneous echocardiograms from two different heart valves, together with phonocardiograms, were recorded on an Irex Multichannel Recorder and the products of this new technique are hereafter referred to as simultaneous dual echophonocardiograms. The procedure may be carried out either by one operator holding one echo transducer in each hand or by two operators each directing a single transducer. Each transducer is connected to a SmithKline Ekoline 20 Ultrasonoscope and the two ultrasonoscopes are interfaced with one Irex recorder. The technique is facilitated when more than one interspace is available for obtaining satisfactory echocardiograms, but we have obtained successful recordings from two transducers placed in the same interspace. A disadvantage of the result resulting from this technique is the presence of an interference pattern caused by the transducers picking up ultrasound signals from each other. This interference is maximal when the transducers are pointing in the same direction and minimal when they are pointing in diametrically opposite directions. During the study, a modification of the technique was developed by which the two echoscopes were electronically integrated to pulse ultrasound in phase with each other. This resulted in abolition of the interference although avoidance of superimposition of the echo images became more difficult.

Combined Echo and Hemodynamic Studies

Six patients were studied during cardiac catheterization when echo and phonocardioograms were obtained simultaneously with high fidelity intracardiac pressures. All such pressures were obtained from Millar catheter-tip micro-manometer catheters. When two simultaneous catheter pressures in different chambers were recorded, the catheters were rendered equisensitive in one of the chambers immediately prior to the recording.

Patients

Group 1. Combined Hemodynamic-Echo Studies Relating A-V Valve Movement to Intracardiac Pressure Changes

In six patients undergoing diagnostic cardiac catheterization, we investigated the relationship between: a) right atrial, right ventricular pressure crossover and tricuspid valve closure, and b) left atrial, left ventricular pressure crossover and mitral valve closure. The right heart studies were carried out in five patients — two had an atrial septal defect (ASD), two had severe mitral stenosis, and one had a left ventricular-right atrial shunt. The left heart study was performed in another patient with an ASD when the left atrial pressure was obtained by passing the catheter across the defect from the right atrium.

Group 2. Studies of the Contribution of Tricuspid Valve Closure to S1

A total of 11 patients were studied to assess the contribution of closure of the tricuspid valve to the first heart sound.

Figure 1. Relationship between tricuspid valve closure (TVC) and RA/RV crossover (arrowed vertical lines). The first and third beats show a delay of 50 msec from RA/RV pressure crossover to completion of TVC. The second beat is a premature ventricular contraction (PVC) showing prolongation of this delay (75 msec) associated with reduced RV dP/dt. Beat 3 illustrates lag between pressure crossover and start of rapid phase of valve closure (heavy line) in this patient in atrial fibrillation. ALTV = anterior leaflet of tricuspid valve, PCG-LSE = phonocardiogram at left sternal edge, ECG = electrocardiogram. Recording speed 200 mm/sec; time lines 10 msec.
Group 2B consisted of five patients in whom either a hemodynamic or a conduction abnormality allowed separation of tricuspid and aortic valve events. The two essential criteria for inclusion in group 2 were 1) that a high quality echocardiogram of tricuspid valve closure could be obtained, and 2) that there was no known abnormality of the aortic valve which might have been responsible for an aortic valve ejection sound — a phenomenon not under study in the present work. The diagnoses of the patients in group 2A were as follows: 2 patients had mitral stenosis, 1 patient had aortic and mitral regurgitation, 1 had an atrial septal defect, 1 had previously closed ventricular septal defect, 1 had Eisenmenger syndrome. The clinical details of the patients in group 2B are presented in the text.

Results

Group 1. Relationship of Mitral and Tricuspid Valve Closure to Pressure Crossover between Atria and Ventricles

Using high fidelity pressures and echocardiography we have studied the time interval between right atrial-right ventricular pressure (RA/RV) crossover and tricuspid valve closure, and left atrial-left ventricular pressure (LA/LV) crossover and mitral valve closure.

RA/RV pressure crossover consistently preceded tricuspid valve closure by 35–60 msec with 50 msec being the most consistent interval (fig. 1). A delay of 25 msec was observed between pressure crossover and the start of rapid closure of the tricuspid valve. This lag was particularly obvious in the patient illustrated in whom, because atrial

![Figure 2](image-url)  
**Figure 2.** An echocardiogram of the mitral valve taken during cardiac catheterization. The high fidelity pressure traces show LA/LV pressure crossover (first arrow) preceding mitral valve closure (second arrow) by 50 msec. Time lines 1 sec. MVE = mitral valve echocardiogram.

Group 2A consisted of six patients in whom simultaneous dual echophonocardiograms demonstrated the near synchrony of tricuspid valve closure and aortic valve opening.

![Figure 3](image-url)  
**Figure 3.** Three simultaneous dual echophonocardiograms from a patient with right bundle branch block (RBBB) and a Lillehei-Kaster prosthetic valve in the aortic position. Panel 1 shows closure of tricuspid valve (TVE), upper half, and mitral valve (MVE), lower half, coinciding with two widely separated components of S₁. Panel 2 illustrates that the opening of the prosthesis occurred at the same time as tricuspid valve closure. Panel 3, recorded during right ventricular (RV) pacing shows tricuspid closure still associated with a high frequency sound, separated from prosthetic opening which is silent. The sound labelled M₁ in panel 3 was demonstrated to coincide with mitral valve closure during pacing. S₁ = closure sound of aortic prosthesis. Recording speed 200 mm/sec; time lines omitted.
fibrillation was present, there was no closing motion of the valve following atrial systole. In this patient with a heavily calcified, stenotic mitral valve, tricuspid valve closure was coincident with the onset of the high frequency vibrations of the first heart sound.

A similar relationship between pressure crossover and atrioventricular valve motion was found in the left heart, where LA/LV pressure crossover was found to precede mitral valve closure by 50 msec (fig. 2).

Groups 2A and 2B. The Relationship of Tricuspid Valve Closure to the Second High Frequency Component of S1.

Group 2A

In the majority of patients studied by routine echophonocardiography it is apparent that the completion of tricuspid valve closure and the start of aortic valve opening occur very close together. This observation was confirmed by dual echocardiography in six patients in whom tricuspid valve closure was found to precede the initial separation of the aortic cusps by 15-25 msec. Because of the preceding first component of S1, it is frequently difficult to locate precisely the onset of the vibrations of the second high frequency component. While tricuspid valve closure was found to coincide with the start of the second component of S1, it was impossible to be certain that events occurring at the time of the initial separation of the aortic valve cusps were not playing an important role in the genesis of this sound.

Group 2B

In five patients a variety of cardiac abnormalities, resulting in an alteration in the timing of tricuspid valve closure, permitted the recording of an unequivocal and consistent relationship between this event and the second component of

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**Figure 4.** Recording made during cardiac catheterization: simultaneous high fidelity aortic root pressure, aortic valve echocardiogram and phonocardiogram. The high frequency components of S1 are ended before the start of the rise of pressure in the aorta and the start of opening of the aortic valve (vertical line). Recording speed 200 mm/sec; time lines 10 msec.

**Figure 5.** Simultaneous dual echophonocardiogram from same patient as in figure 4. Tricuspid valve in the upper half and aortic valve (AVE) in the lower half. Interference pattern from the two echo transducers is seen, being more pronounced in the tricuspid portion of the record. On each beat the first vertical line indicates tricuspid valve closure (TVC), the second line the initial moment of aortic valve opening (AVOI) and the third line the completion of aortic valve opening (AVOC) — the timing of aortic valve ejection sounds. PLTV = posterior leaflet of the tricuspid valve. Recording speed 200 mm/sec; time lines 10 msec.
Figure 6. Simultaneous dual echophonocardiogram of aortic and tricuspid valves of a patient with a widely split $S_1$. The second component labeled $T_1$ coincides with tricuspid valve closure and occurs before the initial opening of the aortic valve. The first component labeled $M_1$ was found in other records to coincide with mitral valve closure. Interference pattern from two transducers is again present. Recording speed 200 mm/sec; time lines 10 msec.

$S_1$. Three patients were studied with simultaneous dual echophonocardiograms enabling aortic valve opening to be specifically excluded in these cases.

Case 1. Splitting of $S_1$, coinciding with widely separated mitral and tricuspid valve closure (fig. 3, panel 1), was demonstrated in a patient who developed complete right bundle branch block following insertion of a Lillehei-Kaster prosthesis in the aortic position. Although the opening of this prosthesis does not usually produce a sound which can either be heard or be recorded phonocardiographically, since the opening of the prosthesis coincided with tricuspid valve closure (fig. 3, panel 2) it was not possible to exclude a contribution from prosthetic opening to the sound labelled $T_1$. This could, however, be demonstrated during right ventricular pacing, when the reversal of the normal sequence of ventricular depolarization allowed tricuspid valve closure and an associated high frequency sound, to be separated from aortic prosthetic opening (fig. 3, panel 3), which was now shown to be a silent event.

Case 2. Figures 4 and 5 were recorded from a patient with congestive cardiomyopathy, in whom aortic valve opening was delayed as a result of slow rise of left ventricular pressure. Figure 4 recorded during cardiac catheterization shows that the rise of pressure in the aortic root and the start of opening of the aortic valve recorded echocardiographically occur after the completion of the first heart sound. Figure 5 from the same patient shows that the second component of the first heart sound coincided with tricuspid valve closure and preceded both the initial and the final moments of aortic valve opening, times at which an aortic component of $S_1$ might have been expected to occur.

Case 3. In a patient with splitting of $S_1$ and moderate mitral regurgitation, it can be seen (fig. 6) that the second high frequency component of $S_1$ coincided with tricuspid valve closure and occurred prior to the start of aortic valve opening.

Case 4. Synchrony of echocardiographic mitral and tricuspid valve movements with the two components of $S_1$ was demonstrated in a patient with multifocal ectopic beats. Figures 7 and 8 illustrate the consistent relationship of mitral valve closure to the first high frequency component and tricuspid valve closure to the second component despite a changing array of conduction patterns.

Case 5. Unusual hemodynamic abnormalities may alter the temporal relationship of valvular events with consequent changes in the elements of $S_1$. This is illustrated in figure 9 taken from a patient who had undergone mitral valve replacement and tricuspid valvuloplasty, the latter resulting in tricuspid valve stenosis. The P-R interval was prolonged causing the mitral prosthesis to close during diastole, drift open, and then close again with ventricular systole. The tricuspid valve, being rendered stenotic, shows only a partial closing movement during diastole following the P wave.

Figure 7. A variety of ventricular complexes are seen in this dysrhythmia. Despite the variety of intraventricular conduction defects, a constant relationship is noted between the first high frequency component of $S_1(M_1)$ and mitral valve closure. Time lines 40 msec.
Thus with the onset of right ventricular systole the tricuspid valve is seen to close rapidly, this being associated with a loud high frequency sound (fig. 10).

**Discussion**

During the past two decades, debate over the genesis of the first heart sound has been instrumental in stimulating investigations leading to a better understanding of cardiac physiology.1 The critical question is whether or not the mitral and tricuspid valves play a major role in the genesis of the first heart sound.

An important objection to this hypothesis has been the observation that the point of crossover of the left atrial and left ventricular pressure pulses precedes the onset of the first heart sound. This has been taken to indicate that valve closure occurred at the points of pressure crossover and therefore could not contribute to genesis of the first heart sound.3,7 We have found however, that RA/RV pressure crossover precedes tricuspid valve closure and LA/LV pressure crossover precedes mitral valve closure, by around 50 msec.

The important studies of Laniado et al.13,14 showed that flow across the mitral valve continues for 30-40 msec after LA/LV pressure crossover. These authors postulated that owing to its inertia, blood continues to flow across the mitral valve for a finite time beyond pressure crossover. On theoretical grounds alone, this concept had earlier been advanced by Faber12 and recently developed by Murg.15 Our observation of a delay from RA/RV pressure crossover to the start of rapid closing of the tricuspid valve (fig. 1) supports this concept. Thus, immediately following the corresponding atrioventricular pressure crossovers the mitral and tricuspid valves remain open because of continuing flow. Around 25 msec later, because flow is being reduced by the rising ventricular pressure, the valve begins to close rapidly, and this movement is completed after a further delay of about 25 msec. Thus the observations that the atrioventricular pressure crossovers precede the first heart sound does not exclude an important role for the mitral and tricuspid valves in the genesis of that sound.

A further objection to the concept of an atrioventricular valve contribution to S1 is the observation in dogs that the mitral valve apparatus has insufficient mass to account for the first heart sound.17 Recently, however, we have observed in three different patients with a prolonged P-R interval that closure of the mitral valve prior to the onset of ventricular systole was associated with an audible high frequency sound (fig. 11). A possibility that these were atrial sounds (S1) is excluded by the high frequency of the vibrations and also by the fact that atrial sounds normally occur at the time of maximal opening of the valve as a result of atrial systole.18

This observation that sound production may be associated

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**Figure 8.** The same patient as in figure 7. A constant relationship between the second high frequency component of S1(T1) and tricuspid valve closure is maintained.

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**Figure 9.** Echophonocardiogram of Lillehei-Kaster mitral prosthesis. The P-R interval is 0.30 sec and consequently the prosthesis is seen to make two closing movements during presystole. A high frequency sound (MPC) accompanies closure. MPC = mitral prosthetic click. Time lines 40 msec.
with MV closure in diastole suggests that the normal first heart sound could be accounted for by tension in the mitral valve apparatus occurring when the valve closes under the influence of ventricular systole.

The establishment of a positive role for tricuspid valve closure in the complex of vibrations constituting S₁ has required the study of situations in which normal physiology has been altered. Thus in patients in group 2A although the movements of the aortic and tricuspid valves could be meticulously traced, the temporal proximity of these events precluded the allocation of sound genesis to either. In contrast, in the patients in group 2B we have demonstrated that tricuspid valve closure can be shown to coincide with a high frequency sound, aortic root events being excluded. While these results have been obtained from abnormal hearts, we believe that the continuing association between tricuspid valve closure and the second high frequency component of S₁ in such situations is strong evidence for a causative rather than incidental relationship between these two events. These studies are consistent with earlier observations of a contribution of tricuspid valve closure to the genesis of S₁. The second component of S₁ is often markedly accentuated in patients with an atrial septal defect and becomes softer following closure of the defect.²⁶ The intensity of the sound thus alters in parallel with the amount of flow across the tricuspid valve. In Ebstein's anomaly of the tricuspid valve the second component of S₁ is accentuated and delayed and we have confirmed the observations of others that this sound coincides precisely with closure of the abnormal valve.²⁹,³⁰ A recent study employing right atrial phonocardiography³¹ demonstrated that the second high frequency component of S₁ coincides with the right atrial C wave despite alterations in the pattern of intraventricular conduction.

We believe the results of the present study together with previously published data support the hypothesis that the two major high frequency components of S₁ are intimately related to mitral and tricuspid valve closure, respectively. Recognition of the role of tricuspid valve closure in the genesis of S₁ does not exclude a possible contribution of aor-

tic root events, particularly to the lower frequency vibrations occurring toward the end of S₁.²² It is well recognized that a major high frequency ejection sound occurs at the moment of full opening of bicuspid or stenotic aortic valves.²⁴-²⁶ It has been suggested that aortic root sounds may occur prior to these ejection sounds, that is, at the start of aortic valve opening.²⁶ In view of the observations that we have described above, it would be important to take note of tricuspid valve closure in a study of such sounds and the technique of simultaneous dual echophonocardiography should be useful in such investigations.

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Hemodynamics after Surgical Repair
with Right Ventricle to Pulmonary Artery Conduit

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SUMMARY To assess the results of cardiac repair utilizing a right
ventricular to pulmonary artery conduit, we reviewed postoperative
hemodynamic data in 16 patients catheterized 0.5 to 5 years after
repair. In 12 patients, a Hancock conduit (dacron conduit with por-
cine valve) was used; the conduit in the remaining four patients
was made with an aortic homograft. All patients in whom an aortic
homograft was utilized developed severe obstruction and calcification of
dacron conduit with a porcine aortic valve was used to estab-
lish continuity between the functional right ventricle and the
main pulmonary artery or its major branches.

Material and Methods

Between January 1974 and September 1975, 16 con-
secutive patients with a conduit from functional right ventri-
cle to pulmonary artery underwent cardiac catheterization at
The Children's Hospital Medical Center of Boston.
Catheterization was performed 0.1 to 5 years (mean 1.8
years) following the surgical repair (table 1). Twelve of these
patients had severe forms of tetralogy of Fallot, two patients
had D-transposition of the great arteries with pulmonary
stenosis and a ventricular septal defect, one patient had trun-
cus arteriosus, and one patient had corrected transposition
with pulmonary atresia, and a ventricular septal defect. The
patients' ages at surgery ranged between 2 and 24 years
(mean 11.3 years). The operation was performed at either
the Children's Hospital Medical Center of Boston (13/16
patients) or at the Mayo Clinic (3/16 patients).

In four of the 16 patients, a frozen-irradiated homograft
aortic valve with a segment of the ascending aorta was used
as a conduit to establish continuity between the heart and
pulmonary arteries, while in the remaining 12 patients a
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