The Mechanism of Splitting of the Second Heart Sound in Atrial Septal Defect

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SUMMARY The mechanism underlying the width of splitting of the second heart sound \((S_2)\) was investigated in 27 patients with ostium secundum atrial septal defect (ASD), all of whom had significant left to right shunting. Micromanometer catheters were used to record simultaneous high fidelity right ventricular (RV) and pulmonary arterial (PA) pressures. Electrocardiogram and external phonocardiograms were recorded simultaneously with pressures. \(QP\), \(QA\), and \(Q-RV\) intervals were measured from the onset of the Q-wave of the ECG to the onset of \(P_a\), \(A_s\) and to the downstroke of the RV pressure trace at the level of the pulmonary incisura, respectively. The width of splitting of the second heart sound \((A_s-P_s\) interval) and hangout \((HO)\) intervals were derived by subtracting \(QA\) from \(QP\) and \(Q-RV\) from \(QP\), respectively.

The patients were divided into three groups. There were 14 patients in group I (normotensive ASD) with sinus rhythm and normal PA pressure \((mean<21 \text{ mm Hg})\); in group II (hyperkinetic pulmonary hypertension) there were seven patients with sinus rhythm and elevated PA pressure \((\text{mean PA}>23 \text{ mm Hg})\) and group III consisted of six patients with atrial fibrillation. For normotensive ASD, \(A_s-P_s\) and hangout intervals correlated well \((r=0.91)\) and were essentially equal. \(QA\) and \(Q-RV\) intervals were also approximately equal, indicating that the electromechanical interval was essentially equal for right and left ventricles \((LV)\).

In hyperkinetic pulmonary hypertension the hangout interval was relatively narrow as compared to group I \((P<0.001)\) and the splitting interval varied from narrow to wide, depending upon the relative durations of \(Q-RV\) and \(QA\). The \(QA\) indices tended to be within normal limits, suggesting that the duration of \(Q-RV\) was the major determinant of the width of splitting. In atrial fibrillation, \(HO\) was fixed and narrow; \(A_s-P_s\) and \(Q-RV\) intervals were directly related to preceding cycle length. Thus, an understanding of the mechanism of splitting of the second heart sound in ASD must reflect the \(HO\) interval as well as the relative durations of \(RV\) and \(LV\) electromechanical systoles.

WIDE FIXED SPLITTING OF THE SECOND HEART SOUND \((S_2)\), appreciated as audible expiratory splitting, is a characteristic auscultatory feature of atrial septal defect.\(^1\) Prior studies have demonstrated that this phenomenon is due to a prolonged \(QP\) interval,\(^4\) but the mechanism underlying this wide splitting remains controversial.\(^5\) Prolongation of right ventricular systole due to diastolic volume overload is the most widely accepted mechanism.\(^4\)\(^5\) However, several observations suggest this classic explanation may be only partially correct. First, there are many reports of documented persistence of audible expiratory splitting of \(S_2\) after proven repair of the atrial septal defect.\(^1\)\(^-\)\(^10\) Secondly, wide expiratory splitting of the second heart sound also occurs in idiopathic dilatation of the pulmonary artery, a condition where diastolic overloading is absent.\(^14\) Thirdly, if the abnormal splitting was due to volume overload of the right ventricle, then one would expect a significant correlation between the amount of shunting and the width of splitting. Castle was unable to show such a correlation but he did show that, in children with atrial septal defects, the width of splitting increased as age increased.\(^18\) In light of these observations, the present study attempted to define the mechanism underlying the wide splitting of the second heart sound seen with atrial septal defect.

Materials and Methods

Twenty-seven patients undergoing diagnostic cardiac catheterization were the subject of this investigation. All had isolated ostium secundum atrial septal defects. Six were...
male and 21 were female ranging in age from 14 to 67 years. In each case, specific permission was granted to perform high fidelity intracardiac sound and pressure measurements during the course of the diagnostic study. The diagnosis was confirmed in all patients at catheterization which showed left-to-right shunts of 1.9:1 or greater as determined by oxygen saturations and/or the nitrous oxide inhalation method. Twenty-four of these patients subsequently underwent surgical repair where the diagnosis was confirmed. Patients with ostium primum defects, right ventricular outflow obstruction, or associated mitral regurgitation were excluded.

All patients were studied in the supine position. Intracardiac sound and pressure events were recorded with micromanometer catheters.* These transducers allow recording of high fidelity intracardiac pressure free of contour distortion and without time delay and their audiocircuitry has a flat response from 70 to 2,000 Hz with a roll-off of 12 decibels per octave below 70 Hz. Two catheter-tipped micromanometers were placed in the right ventricle where micromanometric pressures were made equisensitive. One micromanometer was then placed in the pulmonary artery just above the valve from which sound and pressure were recorded. Equisensitivity was checked throughout the study by pullback of the pulmonary artery micromanometer to the right ventricular outflow tract. In three cases where it was specifically checked, there was no difference between the intervals measured with the right ventricular catheter positioned in either the inflow or the outflow portion of the right ventricular chambers. External sound was recorded using an Electronics for Medicine microphone and band pass filters set at 120 and 500 Hz on a DR 12 recorder. The external phonocardiogram was recorded on the chest wall at the point of maximum intensity of the aortic and pulmonic closure sounds and a simultaneous electrocardiogram was obtained for timing purposes. Continuous respirations were monitored with a nasal thermistor. The data were recorded simultaneously on a multichannel Electronics for Medicine photographic recorder at a paper speed of 100 mm/sec with timeline markers indicating 20 msec.

The following intervals were measured on each patient and were the average of at least ten successive complexes taken during quiet respiration (fig. 1):

1) \( QP_2 \) — interval from the onset of the Q-wave of the electrocardiogram to the onset of the pulmonic component of the second heart sound. Intergroup comparisons of \( QP_2 \) intervals were performed using \( QP_2 \) indices calculated from regression data for ASD by Curtiss et al.\(^\text{17}\)

2) \( Q-RV \) (electromechanical interval) — interval from the onset of the QRS to the downstroke of the RV pressure trace at the level of the pulmonary artery incisura.

3) \( QA_2 \) — interval from the onset of the Q wave of the electrocardiogram to the onset of the first high frequency vibration of the second heart sound. The \( QA_2 \) index was obtained using the regression equation of Weissler et al.\(^\text{18}\)

4) EPI (Electropressor interval) — interval from the onset of the QRS to the onset of right ventricular pressure rise.

5) \( A_2-P_2 \) (splitting interval) — \( QP_2 \) minus \( QA_2 \).

6) Hangout interval (HO) — interval separating the right ventricular pressure curve from the pulmonary artery incisura at the pressure level of the latter (\( QP_2 \) minus Q-RV interval).

**Results**

**Group 1: Normotensive Atrial Septal Defect**

This group consisted of 14 patients in normal sinus rhythm with mean pulmonary artery pressures of less than

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\*Millar Mikro-tip pressure transducer; Carolina Medical Electronics.
21 mm Hg (table 1). They ranged in age from 16 to 50 years. All were characterized by wide splitting of the second heart sound and by the presence of a large pulmonary artery on routine chest roentgenogram. The group 1 patients had a mean QA2 index of 552 ± 24 msec (sd). The right ventricular electromechanical intervals ranged from 37 to 45 msec with a mean of 40 ± 2 msec (sd). In this group, the width of splitting was not significantly associated with the degree of shunting but there was close agreement between the hangout interval and the A2-P2 interval (r=0.91). These two intervals never varied by more than 10 msec although the A2-P2 interval ranged from 36 to 66 msec. The QA2 and Q-RV intervals were essentially equal.

Figure 2 is representative of the sound and pressure correlates found in these patients. The width of splitting was 66 msec. P2 was coincident with the incisura of the pulmonary artery pressure tracing which was separated from the right ventricular pressure trace by a hangout interval of 66 msec. The QA2 and Q-RV intervals were both equal to 371 msec.

Group II: Hyperkinetic Pulmonary Hypertension

This group consisted of seven patients with normal sinus rhythm who had elevation of the mean pulmonary artery pressure to a level greater than 23 mm Hg. They ranged in age from 14 to 64 years. They were characterized by an increase in the pulmonary to systemic resistance ratio as com-
pared to group I with significant maintenance of left-to-right shunting (table I). As compared to group I, the right-sided hangout interval was uniformly narrower (25 ± 9 vs 44 ± 8 msec; P < 0.001). Two patients in group II had relatively narrow splitting of S₂ (< 30 msec). The patient whose findings are depicted in figure 3 had a mean pulmonary artery pressure of 55 mm Hg, a pulmonary to systemic flow ratio of 4.5:1, and a normal QA₂ index of 560 msec. Narrow splitting of S₂ was observed on the external phonocardiogram and was associated with a narrow hangout interval of 28 msec. Patient A.G. with a mean pulmonary artery pressure of 30 mm Hg showed a similar narrow hangout interval and a normal QA₂ index. In these two patients, similar to group I subjects, the Q-RV and QA₂ intervals were equal.

Five patients in this group showed wide splitting of the second heart sound indistinguishable from group I. Representative of their findings (fig. 4) shows a narrow hangout interval of 15 msec associated with a splitting interval of 40 msec. In these five patients the mean Q-RV interval was 30 ± 11 msec longer than the mean QA₂ interval contrasting significantly with group I (2 ± 3 msec; P < 0.001). In one patient (A.P.) manifesting the widest splitting of A₂P₂, a considerable proportion of the increased splitting could be ascribed to shortening of QA₂. In the remaining four patients the mean QA₂ (551 ± 18 vs 552 ± 24 msec; II vs I) and QP₂ indices (634 ± 11 vs 635 ± 28 msec; II vs I) were essentially the same as in group I. Since the hangout interval was significantly narrower in group II, a significant portion of the wide splitting in this subgroup appeared to be due to prolongation of right ventricular electromechanical systole.

Group III: Atrial Fibrillation

This group consisted of six patients with atrial fibrillation ranging in age from 53 to 67 years. Their mean pulmonary artery pressures averaged 22 mm Hg (range: 18 to 26 mm Hg). The splitting interval in these patients varied directly with the preceding R-R cycle length (fig. 5) but the hangout interval was relatively narrow and remained constant. Table 2 shows the effect of preceding cycle length on various intervals in patient V.W. With preceding cycle lengths of 468 to 1096 msec, the splitting interval varied from 34 to 72 msec. The hangout interval was relatively narrow and remained constant at 22 msec. For cycle lengths of 468 to 740 msec, QA₂ and Q-RV increased but the increments were greater for the latter, resulting in wider splitting. From 829 to 1096 msec, Q-RV continued to increase as QA₂ remained constant, further increasing the width of splitting.

Discussion

The hallmark of patients with normotensive atrial septal defects is wide, fixed (respiratory variation less than 20 msec) splitting of the second heart sound attributable to a delayed P₂. Such was the case in the 14 patients comprising group I in this study. The QA₂ index in this group was not significantly different from reported normals. Although every patient in this group showed incomplete right bundle branch block, right ventricular hypertrophy, or a complete right bundle branch block pattern, the right-sided electropressor intervals were within normal limits as reported by Curtiss et al.

For group I, there was a close association between the hangout and splitting intervals on the one hand and the QA₂ and Q-RV intervals on the other. As the hangout interval on
the left is negligible, QA₂ is a good measure of the left-sided electromechanical interval.¹⁹ Therefore the electromechanical intervals for right and left ventricles may be inferred to be almost equal. This suggests that there is a chronic adaptation by the right ventricle which allows it to eject the increased volume load without significantly increasing its duration of systole. Thus, wide splitting of the second sound did not appear to be due to prolongation or shortening of the electromechanical intervals of the right and left ventricles respectively.

The duration of the right-sided hangout interval has been shown to be related to the status of the pulmonary vascular impedance or the total opposition to forward flow.¹⁸ Impedance depends not only on resistance but also on arterial compliance and capacitance. A consequence of the long-standing volume overload on the right side of the circulation is a large dilated pulmonary artery which is characteristic of this disorder. In the normotensive atrial septal defect, with a marked increase in the pulmonary blood flow, there must be a normal or low pulmonary vascular resistance. Thus, the pulmonary vascular bed can be characterized as a high capacitance, low resistance system. It is therefore no surprise that the group of normotensive ASD patients all have in common wide hangout intervals consistent with the low impedance characteristics of the pulmonary vascular tree. Nearly equal durations of right and left ventricular electromechanical intervals coupled with small, absolute values of the normal left-sided hangout interval are responsible for a good correlation between A₂-P₂ and the right-sided hangout interval. Consistent with the hypothesis that the mechanism of wide splitting is related to the dilated pulmonary vascular bed are the numerous reports of persistent abnormal splitting of the second heart sound following repair of the atrial septal defect.¹⁻¹⁵ Further support for this hypothesis is found in the wide audible expiratory splitting of the second sound observed in idiopathic dilatation of the pulmonary artery where there is no volume overloading of the right ventricle.¹⁴

While one can demonstrate a good correlation between splitting of A₁-P₂ and the hangout interval in patients with normotensive atrial septal defect in sinus rhythm, wide splitting of A₁-P₂ in other patients with this defect may be due to

prolongation of right ventricular electromechanical systole. The patients in group III with normal or slightly elevated pulmonary artery pressures who were in atrial fibrillation were found to have nearly constant hangout intervals independent of preceding cycle length. The relatively narrow hangout intervals for this group of patients compared to the normotensive group may be related to an increase in impedance of the pulmonary vascular bed that has been postulated to occur with increasing age.²⁰ Our findings confirm the observation of Aygen and Braunwald that longer R-R cycles are associated with wider splitting of the second heart sound.⁴ Two factors appeared to be responsible for this observation: 1) QP₂ progressively increased with increasing cycle length due to a selective increase in the duration of RV electromechanical systole, and 2) at relatively long cycle lengths, the duration of LV electromechanical systole was relatively fixed. It is possible that the explanation of this finding is related to the differences in compliance between the right and left ventricles. The longer cycle lengths allow greater time for diastolic filling and because the left ventricle is thicker and less compliant than the right, there is selectively more filling of the right ventricle. This greater filling of the right ventricle then leads to selective prolongation of the right ventricular electromechanical interval with increase in the width of splitting of S₂. Our observations do not exclude a significant contribution of abnormal left ventricular function to wider A₁-P₂ splitting. They do document, however, the significant contribution of RV electromechanical systole prolongation to this phenomenon.

The group II patients had hyperkinetic pulmonary

### Table 2. Effect of Cycle Length on Splitting in Atrial Fibrillation

<table>
<thead>
<tr>
<th>Preceding R-R interval (msec)</th>
<th>Q-A₂ (msec)</th>
<th>Q-RV (msec)</th>
<th>Q-P₂ (msec)</th>
<th>HO (msec)</th>
<th>A₁-P₂ (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>468</td>
<td>320</td>
<td>332</td>
<td>354</td>
<td>22</td>
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<tr>
<td>644</td>
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<td>365</td>
<td>413</td>
<td>435</td>
<td>22</td>
<td>72</td>
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</tbody>
</table>

HO = hangout interval.
hypertension. This condition has been reported to be associated with wide splitting of S₂ by several observers. Our cases in group II show that a wide range of splitting can be seen. With hyperkinetic pulmonary hypertension the hangout interval becomes narrower, probably related to increased impedance to pulmonary flow. The splitting interval then becomes a function of the relative electromechanical intervals of the left and right ventricles. If they are approximately equal as in two of our group II patients (N.R. and A.G.), the splitting interval will be narrow. Wide splitting can be due to several mechanisms, shortening of the left ventricular electromechanical interval, lengthening of the right ventricular electromechanical interval, or both. While the second mechanism appeared to predominate in this subset of group II, the number of patients was too small to permit adequate assessment of relative prevalence.

Concepts derived from this study relating to the splitting of the second heart sound in ASD are summarized in figure 6. In normotensive ASD, the electromechanical intervals of left and right ventricles are essentially equal and wide splitting of the second heart sound correlates well with the rightsided hangout interval. With hyperkinetic pulmonary hypertension the hangout interval narrows, but the right ventricular electromechanical interval may be either normal or prolonged, tending to result in narrow or wide splitting, respectively. Thus the wide spectrum of splitting of the second heart sound encountered in ASD can most often be explained by taking into account the hangout interval as well as the relative durations of RV and LV electromechanical systoles.

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Radiographic Assessment of Leaflet Motion of Gore-Tex Laminate Trileaflet Valves and Hancock Xenograft in Tricuspid Position of Dogs

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SUMMARY Six samples of various thicknesses of Gore-Tex compounds were fashioned into trileaflet valves. A radiopaque marker was placed on the center of the free margin of each cusp, and the prostheses were implanted in the tricuspid position of dogs. Two Hancock valves were studied for comparison. Catheterization revealed that the hemodynamic function was normal in all valves tested. High-speed radiography permitted analysis of leaflet movement throughout the cardiac cycle. Of the six Gore-Tex valves, five opened completely. The cusps of these five valves were fabricated from 4, 6, 8, 10, and 12 layers of Gore-Tex film. The remaining valve, which was fabricated from 15 layers of Gore-Tex film, and both porcine xenograft aortic valves did not open completely. We postulate that the laminates of 12 layers or less of Gore-Tex film are suitable for further study to evaluate their potential applicability in trileaflet cardiac valve prostheses.

SUBSTANTIAL EFFORT has been directed toward duplicating the natural aortic valve configuration as a model for the ideal valve substitute. Minimal flow resistance and turbulence are the principal theoretic advantages of the central orifice design. In practice, however, once the pathologic processes responsible for leaflet stiffening occur, these hemodynamic benefits are lost and function deteriorates. Hence, the question is raised whether the use of materials, which are initially "too stiff" for valve cusp construction, might likewise contribute to valve failure.

Increasing evidence supports the concept that the longevity of a leaflet-type heart valve substitute depends not only on the mechanical strength and biological and chemical characteristics of the materials employed but also on the design, especially the mode of valve function in vivo. Hydrodynamic function of a model aortic valve has been investigated with a pulse-duplicator, or an in vivo ultrasonic technique. We believe that further progress toward a rational choice of an appropriate leaflet material requires documentation of the valve performance characteristics in the beating heart.

In this study, we used stented trileaflet valves fabricated of Gore-Tex laminate. Gore-Tex (or expanded polytetrafluoroethylene) is a new synthetic material that possesses high tensile properties. Its biocompatibility has been studied in arterial and venous grafts. Additionally, Gore-Tex laminate allows use of materials with a wide range of thickness. We used porcine xenograft aortic valves for comparisons. The purpose of this paper is 1) to describe the initial function of these valves in the tricuspid position of dogs assessed by radiopaque markers and high-speed X-ray techniques; 2) to define the thickness of Gore-Tex laminate that is optimal for a flexible leaflet prosthesis; and 3) to discuss the implications of hemodynamics for adequate long-term function.

Material and Methods

Gore-Tex laminate is manufactured by W. L. Gore and Associates. A single film of this polymer, 0.003-mm thick, consists of nodules and fibrils of polytetrafluoroethylene (PTFE) and has uniaxial tensile strength that parallels the fibril content. The tensile strength of a single film is 60,000 psi — approximately 20 times that of conventional PTFE. For use as valve leaflets, several films are laminated in diverse directions to compensate for the absence of the tensile strength in the cross-directional axis and to add strength. The Gore-Tex laminate is nonporous and transparent, unlike the Gore-Tex vascular prosthesis, which is microporous and snow white. The number of laminated films used in each valve leaflet studied determines the thickness, strength, and stiffness. Six samples constructed from laminates of 4, 6, 8, 10, 12, and 15 layers of Gore-Tex film were studied. These samples ranged from 0.008 to 0.031 mm in thickness as a result of compression during the laminating process.
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