Intracardiac Pressure-Flow Dynamics in Isolated Ventricular Septal Defects

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SUMMARY
This study was conducted to determine the nature of intracardiac shunting in 50 patients between the ages of 3 and 15 years with isolated ventricular septal defects. Simultaneous right and left ventricular pressures and biplane cineangiography were utilized to study the timing and the direction of flow across the defect. Patients with low to moderately elevated right ventricular pressures demonstrated left-to-right shunting across the defect throughout the cardiac cycle. When pressure in the right ventricle approximated that of the left, right-to-left shunting occurred across the defect into the left ventricle during isovolumic relaxation. All patients shared in common the following: (1) a predominant left-to-right gradient and shunt across the defect into the body of the right ventricle during diastole; and, (2) augmentation of the left-to-right gradient with resultant increase of the shunt into the right ventricle during isovolumic contraction immediately preceding opening of the aortic valve.

In comparing patients with and without pulmonary hypertension, the major variations in the cardiac cycle occurred during the periods of ventricular ejection and isovolumic relaxation. These two periods are primarily affected by the changing relationships of the size of the defect, ratio of pulmonary to systemic resistance, and magnitude of net shunts.

Additional Indexing Words:
Cineangiography Congenital heart disease Phonocardiography

It is now generally accepted that the clinical course and underlying physiological state in patients with isolated ventricular septal defects are primarily determined by the size of the defect and the state of the pulmonary vascular bed.\textsuperscript{1-3}

Although the patterns of shunting into the pulmonary and systemic circuits are well known, little information is available concerning the intracardiac dynamics in these patients. This investigation was conducted (1) to determine local shunting mechanisms across the defect itself, and (2) to evaluate whether intracardiac shunting occurs in a more complex fashion than is evident from the knowledge of net shunts into the pulmonary and systemic vascular beds.

Methods
The interventricular pressure-flow relationships across the defect in a group of 50 patients between the ages of 3 and 15 years who had an isolated ventricular septal defect were studied. Cardiac catheterization was carried out under light nitrous oxide anesthesia with the patient in the supine position. Systemic and pulmonary blood flows were calculated from blood-oxygen
saturation data (Fick principle) and from peripherally recorded dye-dilution curves following injection of indocyanine dye into the right atrium and pulmonary artery.

Inspired air and blood oxygen content were measured with an Instrumentation Laboratories 113 $\text{PO}_2$, $\text{PCO}_2$, and pH meter. The inspired air was monitored intermittently and the oxygen concentration was maintained between 20.5 and 21.0 volumes per cent.

Precordial phonocardiograms were recorded in all patients prior to cardiac catheterization; no intracardiac phonocardiograms were obtained.

The methods were divided into three groups: (a) determination of the simultaneous pressures between the two ventricles and their instantaneous pressure difference throughout the cardiac cycle; (b) evaluation of the direction and timing of flow across the defect by use of biplane cineangiocardiology; and (c) correlation of the timing and direction of the shunt across the defect with the instantaneous pressure difference between the two ventricles.

**Pressure Recording and Data Processing Methods (Fig. 1)**

Simultaneous right and left ventricular lateral pressures were measured with no. 6 or 7 catheters having two lateral pressure taps and the ends sealed. The catheters were matched for equal length, volume, and transmission time. The right ventricular catheter was passed to the heart via the superficial saphenous vein, and the left ventricular catheter, via the femoral artery. The catheter recording systems included Statham P23Gb pressure transducers connected to Sanborn 350-1100 preamplifiers. The static unbalance of both systems was no greater than ± 0.1% over the range of 0 to 300 cm of water.

The dynamic system consisted of matched catheter-recording systems for recording left and right ventricular pressures simultaneously (A). The pressures were monitored by a Sanborn multichannel system which recorded the data graphically (B) and on magnetic tape (C). The procedure was monitored oscillographically (D) to ensure valid data acquisition. The tape-recorded data were transcribed by an analog-to-digital converter (E) and then analyzed by an IBM 7072 digital computer (F) which determined the instantaneous values at 1.08 msec intervals for the simultaneously recorded right and left ventricular pressures, their instantaneous pressure difference, and the first derivative of the two pressures (rate of change). These data were then outputted in numeric form (G) and graphic (H) form, the latter by means of a Calcomp plotter.

*Figure 1*

Pressure recording and data processing methods. Matched catheter-recording systems were utilized to measure left and right ventricular pressures simultaneously (A). The pressures were monitored by a Sanborn multichannel system which recorded the data graphically (B) and on magnetic tape (C). The procedure was monitored oscillographically (D) to ensure valid data acquisition. The tape-recorded data were transcribed by an analog-to-digital converter (E) and then analyzed by an IBM 7072 digital computer (F) which determined the instantaneous values at 1.08 msec intervals for the simultaneously recorded right and left ventricular pressures, their instantaneous pressure difference, and the first derivative of the two pressures (rate of change). These data were then outputted in numeric form (G) and graphic (H) form, the latter by means of a Calcomp plotter.
response of the system was evaluated in a sinusoidal pressure generator and was found to be over-damped and flat to 7 cps. The catheter impulse transmission time was 5 to 10 msec. The characteristics of the entire system approached the dynamic response criteria for pressure gradient determinations as outlined by Greenfield and Fry. No attempt was made to measure the distance between the catheter holes. We consider the frequency response sufficient to allow the major details of the first derivative and gradient data to be computed.

The ventricular pressures and electrocardiogram were recorded simultaneously on photographic paper and by a Sanborn FM tape recorder (frequency response flat to 1250 cps). Prior to and after each recording, zero base-line conditions referenced to the midchest position were checked to ensure that there were no baseline shifts. To ensure the validity of the varying pressure gradients throughout the cardiac cycle, each recording was repeated after reversal of the catheter positions. In each instance, the final analysis showed identical pressure gradient contours.

The originally recorded tape data were transcribed by an Airborne Instrument Laboratories analog-to-digital converter at a rate of 926 samples per channel per second. The digital tapes were then analyzed by an IBM 7072 digital computer which determined the instantaneous values at 1.08 msec intervals for the following: the simultaneously recorded right and left ventricular pressures, the instantaneous pressure difference (pressure gradient), and the first time derivative of the two pressures (rate of change). The instantaneous values of the first derivative for each point were calculated on the basis of the pressure difference over an interval of 10 msec. All data were printed in numeric form and were displayed in analog form by a Calcomp plotter.

Methods for Determination of Direction and Timing of Flow (Fig. 2)

To study the timing and direction of flow across the defect, biplane cineangiocardiology was chosen because of the rapid response time that it provides with 5 msec frame exposures at the rate of 60 frames per second. This technique has previously been reported in detail. In summary, 75% Hypaque (sodium and meglumine diatrizoate), 1 ml/kg of body weight, was injected into each ventricle. In order to relate the timing of the shunt to the cardiac cycle, a special photocell device was used in the beams of both the anteroposterior and lateral image amplifier tubes. The outputs of the photocells were simultaneously recorded with the electrocardiogram graphically and on magnetic tape. Injections accompanied by premature ventricular beats were excluded from analysis. To determine that the injection of contrast material did not significantly alter the hemodynamics or shunting, injections were given to 15 patients either into the left atrium or pulmonary artery while simultaneously recording the instantaneous pressure difference between the two ventricles. The pattern of flow across the defect was the same as with left ventricular

![Figure 2](http://circ.ahajournals.org/)

Data recorded during biplane cineangiocardiology. All data were recorded photographically at a low paper speed (A) and simultaneously on magnetic tape for playback with expansion of the time scale (B). The arrow indicates the beginning of injection of contrast medium into the left ventricle. (A) Data recorded during cine studies at slow paper speed. The outputs of the anteroposterior and lateral cine photocell timing device were recorded simultaneously with the electrocardiogram and right ventricular pressure. (B) Replay from magnetic tape with expansion of the time scale. This demonstrates the 60 per second individual photocell cine spikes for the anteroposterior and lateral image amplifier tubes which could be related to the electrocardiogram and right ventricular pressure.
injections, and the pressure gradient pattern remained similar to its pre-injection state. Because of the possible effects of respiration, all patients were studied during periods of apnea.

Correlation of Flow with Instantaneous Pressure Difference

The correlation of the onset and direction of flow across the defect with the pressure gradient was performed by using the electrocardiogram as the common time base. The recording of the pressure data and the cineangiograms were done in sequence. The selected cine frames were related to the cine spikes, as obtained from the photocell device previously described, and the time relationship to the electrocardiogram was noted (fig. 2). After previously determining the catheter response delay time, this point on the electrocardiogram was in turn related to the reproduced ventricular pressure recordings and their instantaneous pressure difference. Thus, each cine frame could be related in real time to the pressure gradient. It should be emphasized that no attempt was made to quantitate precisely the magnitude of flow across the defect in various portions of the cardiac cycle. The correlation of flow with pressure difference was concerned with the timing of the onset of a pressure gradient favoring either ventricle and the onset of flow across the defect in the direction suggested by such a gradient.

Results

On the basis of the following results, the intracardiac pressure flow dynamics demonstrated a consistent pattern within each of three homogeneous groups of patients: (1) patients in whom the left-to-right shunt comprised between 50% and 70% of total pulmonary blood flow in the presence of normal to moderately elevated right ventricular systolic pressures; (2) patients in whom the left-to-right shunt varied between 40% and 60% of total pulmonary blood flow and the right ventricular systolic pressure was raised to 70 mm Hg or greater but remained 15 to 30 mm Hg less than peak left ventricular pressure; and (3) patients in whom bidirectional shunting was present with “equal” systolic pressures in both ventricles.

Large Left-to-Right Shunts with Normal to Moderately Elevated Right Ventricular Systolic Pressures (Twenty-eight Patients)

During diastole, there were fluctuations in pressure which remained predominantly in favor of the left ventricle (fig. 3). With the onset of isovolumic contraction, left ventricular pressure rose before, or more rapidly than, that of the right ventricle with marked accentuation of the pressure difference; this large left-to-right gradient was maintained throughout the period of ventricular ejection. As the pressures approximated each other at the end of isovolumic relaxation, the left ventricular pressure transiently fell below that of the right ventricle in some patients.

Figure 3

Interventricular pressure relationships in patients with large left-to-right shunts with normal to moderately elevated right ventricular systolic pressures. These data were outputted by a Calcomp plotter following analysis by the digital computer of the tape recorded left and right ventricular pressures. (A) The left (LV) and right (RV) ventricular pressures reconstructed by the Calcomp plotter. (B) First derivatives of the left (LV) and right (RV) ventricular pressure curves. Note the more rapid rise and greater positive magnitude in the left ventricular derivative during isovolumic contraction as well as the more rapid fall and greater negative magnitude during isovolumic relaxation as compared to that of the right ventricle. (C) The instantaneous pressure difference (pressure gradient). Note the left ventricular pressure predominance throughout the cardiac cycle. See text for discussion.
Cine data indicated left-to-right shunting throughout the cardiac cycle; there was no right-to-left flow across the defect at any time. During diastole, left-to-right shunting across the defect occurred directly into the body of the right ventricle, with this flow being accentuated following atrial contraction. There was further augmentation of the left-to-right shunt with the onset of isovolumic contraction. Following opening of the pulmonic valve, the period of ventricular ejection was characterized by the left-to-right shunt being directed across the outflow tract of the right ventricle into the pulmonary artery. This shunting continued during isovolumic relaxation. Review of the pictures in motion showed that immediately following closure of the pulmonic valve, this flow changed direction and occurred into the body of the right ventricle. A few patients showed transient cessation of the left-to-right shunt at the completion of isovolumic relaxation; this phenomenon was associated with a transient right-to-left gradient in the absence of right-to-left shunting.

**Defects with a 15 to 30-mm Hg Systolic Pressure Gradient Between the Ventricles (Seven Patients)**

These patients had peak right ventricular systolic pressures of 70 mm Hg or greater, yet a pressure gradient of 15 to 30 mm Hg remained across the defect during ventricular ejection. Figure 4 demonstrates the simultaneously recorded ventricular pressures, their rate of change, and the continuous pressure difference across the defect. During diastole, the pressure gradient was predominantly in favor of the left ventricle. The onset of isovolumic contraction was characterized by an earlier onset or more rapid rise, or both, in the left ventricular pressure as compared to that of the right, with accentuation of the left-to-right pressure gradient. Throughout ventricular ejection there was maintenance of a 15 to 30-mm Hg left-to-right pressure gradient. With the onset of isovolumic relaxation, left ventricular pressure fell more rapidly than that of the right ventricle (fig. 4 B), producing a transient right-to-left gradient at a time when all valves were closed. During diastole, the predominant left-to-right pressure gradient was reestablished. In addition, pressure gradients between the right ventricle and aorta were recorded in all of these patients; during systole, the right ventricular pressure remained below that of the aorta throughout ventricular ejection.

Right and left ventricular cineangiocardiograms demonstrated that left-to-right shunting occurred into the body of the right ventricle during diastole. Augmentation of this

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*Figure 4*

Interventricular pressure relationships in patients with 15 to 30-mm Hg gradients across the defect during ventricular ejection. (A) The left ventricular pressure (LV) remains above that of the right ventricle (RV) throughout the cardiac cycle, except for the period of isovolumic relaxation, when it falls below the right ventricular pressure. (B) The left ventricular (LV) first derivative curve rises before or more rapidly, or both, than the right (RV) during isovolumic contraction and falls more rapidly than the right during isovolumic relaxation. (C) The instantaneous pressure gradient between the left and right ventricles shows a predominant left ventricular gradient during diastole. The left-to-right gradient is augmented during isovolumic contraction and maintained throughout ventricular ejection. The boxed-in area containing the transient gradient in favor of the right ventricle during isovolumic relaxation is reproduced in figure 5.
flow was associated with the increasing left-to-right pressure gradient during isovolumic contraction. As in the previous group, shunting across the defect during ventricular ejection was directed across the outflow tract of the right ventricle. In isovolumic relaxation, all of these patients demonstrated a transient right-to-left shunt into the outflow tract of the left ventricle (fig. 5). With the commencement of diastole, the pressure relationships across the defect favored the left ventricle and flow again occurred in the left-to-right direction across the defect. In these patients, the small volume of blood which was shunted into the left ventricle during isovolumic relaxation was returned to the right ventricle during diastole. All of these patients failed to demonstrate evidence of a systemic right-to-left shunt with peripherally recorded dye-dilution curves.

Defects with “Equal” Systolic Ventricular Pressures (Fifteen Patients)

These patients formed a homogeneous group with a consistent pressure-flow pattern, despite considerable variation in pulmonary vascular resistance and in the degree of the left-to-right shunting. In six patients, with pulmonary-to-systemic resistance ratios greater than 0.7, the bidirectional shunts were equal, or predominant right-to-left shunting was present. In the remaining nine children, the resistance ratios were less than 0.6 and left-to-right shunts comprised 40% to 60% of the total pulmonary blood flow.

The typical pressure pattern found for this group is illustrated in figure 6. With the onset

Figure 5

Timing of the right-to-left shunt across the ventricular defect in patients without systemic veno-arterial shunting. The boxed-in area of figure 4 is illustrated at the top. Below are the timed cine frames related to various points of the gradient curve. Although the right-to-left shunt occurs across the defect during isovolumic relaxation, note clearing of the shunted contrast material from the left ventricle during late diastole due to diastolic left-to-right shunting across the defect.
Intracardiac pressure relationships in patients with “equal” systolic ventricular pressures. (A) Note that the right ventricular pressure (RV) exceeds that of the left (LV) during the latter third of ventricular ejection and remains above it throughout isovolumic relaxation. (B) The left ventricular first derivative (LV) shows a more rapid rise during isovolumic contraction and a more rapid fall during isovolumic relaxation when compared to the right ventricular first derivative (RV). (C) The instantaneous pressure gradient shows a small pressure gradient favoring the left ventricle in diastole, with augmentation during isovolumic contraction (boxed-in area 1). The period of late ventricular ejection was characterized by a small right ventricular pressure gradient which was augmented during isovolumic relaxation (boxed-in area 2).

of isovolumic contraction, there was augmentation of the left-to-right gradient which was primarily due to a more rapid rise in left ventricular pressure as compared to that of the right. During ventricular ejection, the left-to-right gradient was maintained initially, although it diminished as ejection continued. During the latter part of this period, right ventricular pressure exceeded that of the left ventricle. Isovolumic relaxation was characterized by further augmentation of the right-to-left pressure gradient as left ventricular pressure fell more rapidly than that of the right.

Cine studies indicated a consistent pattern related to the timing and direction of flow across the defect in these patients, despite considerable variation in the magnitude of the bidirectional shunts. Figure 7 demonstrates augmentation of the left-to-right shunt during isovolumic contraction (boxed-in area 1 of figure 6), before opening of the aortic valve. With commencement of ventricular ejection, left-to-right shunting continued across the defect and was directed into the outflow tract of the right ventricle. Although analysis of the cine data allowed detection of the onset of shunting across the defect with facility, it was difficult to define the precise time of cessation of left-to-right shunting; however, the cines suggested that shunting into the outflow tract diminished or stopped during the latter part of systole, at a time when right ventricular pressure exceeded that of the left. As the cycle continued into isovolumic relaxation (boxed-in area 2 of figure 6), the more rapid fall in left ventricular pressure accentuated the right-to-left gradient and was associated with right-to-left shunting into the left ventricle (figure 8). This blood seemed to mix in the upper portion of the left ventricle, remained there despite diastolic left-to-right shunting, and was ejected from this chamber into the aorta with the subsequent beat.

The precise timing of flow directly from the right ventricle into the aorta also proved difficult with the cine method following right ventricular and right atrial injections. This was due in large part to the isovolumic relaxation with right-to-left shunting into the left ventricle, which ejected the contrast media into the aorta; however, in three patients, ejection of blood into the aorta could be seen to occur in the latter part of ventricular ejection at a time when right ventricular pressure exceeded that of the aorta. Additionally, during this late ejection period, when left ventricular pressure was less than that of the aorta and right ventricle, there was no shunting in a right-to-left direction across the defect into the...
Figure 7

Left-to-right shunt across the ventricular defect during isovolumic contraction in patients with "equal" ventricular systolic pressures. The reproduced pressure gradient of boxed-in area 1 of figure 6, at the top, with the time related cine frames shows accentuation of the left-to-right shunt during isovolumic contraction before opening of the aortic valve. These films were obtained following injection of contrast media into the left ventricle.

Discussion

Of paramount importance in the management of patients with ventricular septal defects is the understanding of the interplay between resistance to flow created by the defect itself and that offered by the pulmonary vascular resistance in determining the magnitude of left-to-right shunting.1-3 Moderate-sized defects are sufficiently large to permit a large shunt, yet small enough to offer some resistance to flow. Although there may be variation in the size of the defect in this group, the work of Savard and associates indicates that most of these defects are less than 1 cm²/m² BSA. In large defects (greater than 1 cm²/m² BSA), the defect offers essentially no resistance to flow;* the pulmonary circulation is subjected to the prominent ejectile force of both ventricles during most of the period of ventricular ejection, and the magnitude of left-to-right shunting is determined by the level of pulmonary vascular resistance. These studies have indicated that the pattern of flow across the defect itself is also influenced by these parameters with the timing and direction of intracardiac shunting being primarily related to the systolic pressures of the two ventricles.

Since all patients with ventricular defects demonstrated shunting across the defect during the periods of "isovolumic" contraction and relaxation when all valves are closed, the term "isovolumic" presents a semantic

*Although large defects allow equal pressures, an occasional patient may have a systolic gradient of 15 to 20 mm Hg across a large opening.
problem in this situation. Although this term can be accurately applied to the cardiac cycle in patients with competent semilunar and atrioventricular valves and in those with an intact ventricular septum, if there is a communication between the two ventricles, this term becomes inaccurate. The period of “isovolumic” contraction is associated with a decreasing left and an increasing right ventricular volume. The changing volume characteristics of the ventricles during “isovolumic” relaxation are primarily affected by the relationship of the ventricular systolic pressures. During this interval in the presence of low right ventricular systolic pressures, continued left-to-right shunting results in a decreasing left ventricular volume; whereas in patients in whom right ventricular systolic pressure approximates that of the left, this interval is associated with right-to-left shunting and increasing left ventricular volume. We now prefer to designate these intervals for each ventricle as initial contraction and initial relaxation periods of the cardiac cycle, although this nomenclature has the obvious deficiency of not including the time limitation of opening of the semilunar and atrioventricular valves, respectively.

**Defects with Right Ventricular Systolic Pressures Less than 65 mm Hg**

In some of the patients, the “continuous” left-to-right shunt (fig. 3) stopped transiently at the end of isovolumic relaxation when left ventricular pressure fell below that of the right. None of these patients demonstrated right-to-left shunting across the defect at this time. Thus, the development of a transient gradient in favor of the right ventricle may...
be related to the deceleration of the mass of blood and does not signify a right-to-left shunt. Phonocardiographic studies in this group (fig. 9 A) demonstrated a holosystolic murmur that was associated with a large pressure gradient across the defect which lasted throughout ventricular ejection. Several of these patients had an apical diastolic murmur which probably was due to flow across the mitral valve. However, these studies did not exclude the possibility of shunting across the defect as a cause of the diastolic murmur. The absence of a murmur generated by left-to-right flow across the defect during diastole is probably related to the lack of turbulence. This can be accounted for by the relatively small quantity of blood being shunted at this time and the absence of a large pressure gradient.

Defects with Right Ventricular Systolic Pressures Approaching but Less than Those of the Left Ventricle

In evaluating the influence of progressive increases in right ventricular systolic pressure on the pressure-flow pattern across the defect, a consistent pattern was found until right ventricular systolic pressure reached a level of 70 to 80 mm Hg. Patients with right ventricular pressures at this level had a left-to-right pressure gradient of 15 to 30 mm Hg across the defect throughout ventricular ejection. This gradient was maintained into the initial portion of isovolumic relaxation; however, a right-to-left gradient and shunt developed rapidly due to the more rapid fall in left ventricular pressure as compared to that of the right ventricle. These patients failed to demonstrate systemic veno-arterial shunting, and this could be explained as follows: (1) The small quantity of blood which was shunted from the right ventricle to the left during isovolumic relaxation was subsequently returned to the right ventricle during diastole. (2) At no time did the pressure in the right ventricle exceed that of the aorta during ventricular ejection. The characteristics of the systolic murmurs of these seven patients were similar to those of patients with lower right ventricular pressures in that the murmur remained holosystolic in nature (fig. 9 A). This can be accounted for by the maintenance of a significant left-to-right pressure gradient throughout the period of ventricular ejection.

Defects with “Equal” Ventricular Pressures

In patients with large ventricular septal defects and “equal” systolic pressures, the timing and direction of the pressure-flow relationships were consistent. This is of interest since knowledge of the timing and direction of flow across the defect itself did not allow separation of the patients with hyperkinetic pulmonary hypertension from those with predominant right-to-left shunting. Work in progress in our laboratory utilizing simultaneously recorded left ventricular pressure data with biplane cineangiocardiograms of the left heart allows construction of the continuous “pressure-volume loop” of the left ventricle throughout the cardiac cycle. Our initial data suggest that although the timing and direction of flow across the defect remained consistent for these patients with “equal” ventricular systolic pressures, during ventricular ejection the magnitude of left-to-right flow across the defect is large in patients with hyperkinetic pulmonary hypertension and small in those who have predominant right-to-left shunting.

These patients demonstrated many similarities in the intracardiac pressure-flow dynamics to those in patients with tetralogy of Fallot,8 in whom the resistance to flow into the lungs is located primarily in the outflow tract of the right ventricle. The major difference found was that in isolated ventricular septal defect a significant left-to-right shunt occurred across the defect during early ventricular ejection, whereas in tetralogy of Fallot such shunting is minimal to absent as both ventricles eject blood into the aorta.

Phonocardiographic studies showed considerable variation in the character of the systolic murmur in this group of patients. Those with hyperkinetic pulmonary hypertension and predominant left-to-right shunting showed a decrescendo murmur which disappeared or was
Figure 9

Phonocardiographic findings in ventricular septal defects with varying physiological states. (A, 1 and 2). These tracings represent the commonly found murmur along the lower left sternal border in patients with small to moderate-sized ventricular septal defects and normal to moderately elevated right ventricular systolic pressures. Note that the murmur (PSM) is holosystolic in nature. The persistence of the murmur throughout systole correlated in these patients with a large left-to-right gradient across the defect throughout the period of ventricular ejection. (B) Large ventricular septal defect with “equal” ventricular systolic pressures and large left-to-right shunt (hyperkinetic pulmonary hypertension). This tracing was recorded from the left parasternal region in the third interspace. In contrast to the previous group, note the decrescendo nature of the murmur (SM) which shows marked diminution or termination before $S_2$. This murmur was recorded from the patient whose ventricular pressures are shown in figure 6. The pressure relationships across the defect during ventricular ejection demonstrated a decreasing left-to-right gradient as ejection continued. During the latter part of this interval (the period shown above with marked diminution or termination of the murmur before $S_2$), right ventricular pressure exceeded that of the left. Blood oxygen saturation and dye-dilution data indicated a left-to-right shunt which comprised 60% of pulmonary blood flow and a right-to-left shunt which comprised 8% of systemic flow. (C) Large ventricular septal defect with marked elevation of pulmonary vascular resistance and equal bidirectional shunt-
markedly diminished in the latter third of systole (fig. 9 B); in those with high pulmonary resistance and predominant right-to-left shunting, the murmur was minimal to absent (fig. 9 C). The low intensity murmurs in the latter group could be generated by the flow across the defect but are more likely to be of the pulmonary ejection type as is commonly seen in patients with pulmonary hypertension.9

As studies of this type are extended, one would expect documentation of some overlap of the patterns found since a select population was studied, that is, children with ventricular septal defects. However, in summarizing these studies, one can state that practically all defects share in common the following: (1) A predominant left-to-right gradient and shunt across the defect into the body of the right ventricle occurs during diastole. (2) Systole is characterized by an earlier or more rapid rise in left ventricular pressure, or both, compared to that of the right ventricle with resultant augmentation of the shunt into the right ventricle immediately preceding opening of the aortic valve. (3) The major variations throughout the cardiac cycle occur during the period of ventricular ejection and isovolumic relaxation. It is these two periods of the cardiac cycle that are primarily affected by the changing relationships of the size of the defect, ratio of pulmonary to systemic vascular resistance, and magnitude of the net shunts.

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Addendum

Although large ventricular defects (> 1 cm²/m²) allow equalization of systolic ventricular pressures, an occasional patient may demonstrate a 15 to 20-mm Hg systolic pressure gradient across the defect with an accompanying holosystolic murmur. We have recently encountered such a patient who demonstrated this phenomenon and a large defect (2 cm²) was found at surgery. The occurrence of a systolic gradient across large defects most likely is due to systolic reduction in size of the defect.

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