Atrial Pressure-Flow Dynamics in Atrial Septal Defects (Secundum Type)

By Aaron R. Levin, M.R.C.P. (Edin.), Madison S. Spach, M.D.,
John P. Boineau, M.D., Ramon V. Canent, Jr., M.D.,
M. Paul Capp, M.D., and Paul H. Jewett, M.D.

SUMMARY
This study was conducted to determine the instantaneous pressure-flow relationships across secundum atrial septal defects. Simultaneous right and left atrial pressures and the pressure difference (determined with an analog computer) were recorded with matched catheter systems. Biplane cineangiocardioigraphy was used to evaluate the timing of the shunts in various phases of the cardiac cycle. These studies indicated that the major left-to-right shunt and pressure gradient occurred over an interval encompassing late ventricular systole and early diastole. Also, there was augmentation of the left-to-right shunt during atrial contraction. Minute right-to-left shunting and pressure gradients occurred at two times in the cardiac cycle: (1) with the onset of ventricular contraction; and (2) during early ventricular diastole (heart rate, 80 to 100 beats/min). Detection of systemic right-to-left shunts by dye curves was enhanced by relatively slow heart rates (prolonged diastasis) which allowed the shunted blood to flow into the left ventricle. The effects of respiration during phasic changes in intrathoracic pressure resulted in an increasing left-to-right gradient during periods of increasing intrathoracic pressure and a fall in the left-to-right gradient across the defect during periods of decreasing intrathoracic pressure.

Additional Indexing Words:
Congenital heart disease  Hemodynamics  Biplane cineangiocardioigraphy  Timing of shunts  Dye dilution curves  Respiratory effect on intracardiac shunts

THE NATURE OF SHUNTING across the defect in patients with atrial septal defects (secundum type) has been of considerable interest to many investigators during the past decade. Of special interest has been the question as to whether the left-to-right shunt across the defect occurs predominantly during ventricular systole or diastole. Until recently, precise studies of shunting mechanisms in patients with secundum atrial defects have been limited by the lack of sufficiently good technical methods. The present study was undertaken (1) to determine the nature of pressure-flow relationships of the left-to-right shunt at the atrial level, and (2) to evaluate the dynamics responsible for the well-known minute right-to-left shunt.

Methods
Twenty-six children between the ages of 3 and 14 years were studied under light nitrous oxide anesthesia in the supine position at preoperative cardiac catheterization. At subsequent cardiac surgery, all patients were proven to have secundum atrial septal defects which varied in diameter from 1.5 to 3 cm. None of the patients had partial anomalous pulmonary venous drainage or other associated cardiac lesions.
The magnitude of the left-to-right shunt and the cardiac output were determined by the Fick method. The oxygen content of inspired air and blood was measured with an Instrumentation Laboratories 113 pCO₂, pO₂, and pH meter. The inspired air was sampled intermittently to maintain the oxygen concentration between 20.5 and 21.0 vol%. Peripheral arterial dye-dilution curves, with injection of indocyanine green (Cardio-Green) at the inferior vena cava-right atrial junction, were used to detect the presence of small systemic right-to-left shunts.

The methods employed in determining the pressure-flow relationships across ventricular defects in tetralogy of Fallot and isolated ventricular septal defects have been described previously in detail and have been adapted for use in the present study. Briefly, these fall into three categories: (1) the determination of the continuous pressure difference across the defect throughout the cardiac cycle with an analog computer; (2) the timing of flow utilizing biplane cineangiography; and (3) the correlation of the direction of flow with the pressure gradient across the defect.

1. To determine the instantaneous pressure relationships between the two atria, no. 6 or 7 NIH catheters, with side holes and the ends sealed, were matched for equal length, volume, and transmission time and passed to the atria via the right saphenous vein. They were connected to Statham P23Gb pressure transducers which were fed to Sanborn 350-1100 preamplifiers. The simultaneous outputs of each of the preamplifiers were fed to a Heathkit EC-1 analog computer which subtracted the pressure of the right atrium from that of the left. The continuous pressure difference (output of analog computer) was fed back to the recorder for simultaneous recording with the electrocardiogram and both atrial pressures (fig. 1). The characteristics of the system approached the criteria for pressure gradient determinations as outlined by Greenfield and Fry. Prior to and after each recording, zero base-line conditions referenced to the mid-chest position were checked to ensure that there were no base-line shifts. To ensure the validity of the varying pressure gradients throughout the cardiac cycle and to exclude the possibility of artifactual pressure differences, each recording was repeated following reversal of the catheter positions. In each instance, similar gradients were obtained. In 10 patients simultaneous left and right ventricular pressures were recorded with the venous catheters. Pressure determinations in each patient were made during apnea, intermittent positive pressure breathing, and sustained positive pressure insufflation. Intrathoracic pressure was monitored in five patients with a small intra-esophageal balloon according to the method of Milic-Emili and co-workers. During periods of data accumulation, this pressure was −0.1 to −0.6 mm Hg (apnea). During the latter portion of the study, four patients were studied with Statham-Ford pressure transducer-tipped catheters. The results were the same as those obtained with the fluid-filled catheters, with allowance for correction of impulse transmission time.

2. Shunting across the atrial defect was studied by means of selective biplane cineangiography which provided a sampling rate of 60 frames/sec with a 5-msec individual frame exposure. Injection of 75% Hypaque (sodium and meglumine diatrizoate) at 1 ml/kg of body weight was performed into the left atrium, pulmonary veins, or pulmonary artery to study the left-to-right shunt and into the proximal inferior vena cava to study the right-to-left flow across the defect. 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 to record the individual pulses of the cine frames. These were recorded with the electrocardiogram (fig. 2A) which allowed the individual cine frames to be related to the pressure gradient recorded immediately prior to cineangiography. All data were recorded simultaneously in graphic form and on magnetic tape for playback with expansion of the time scale (fig. 2B). The cineangiograms were made during periods of apnea.

The study of intracardiac shunts by any presently available method must alter the phenomenon to some degree by the study itself. Since the injection of contrast media may alter cardiac dynamics, careful checks were made in 12 patients to determine whether the injection of contrast media significantly altered the pressure gradient pattern across the defect during evaluation of the shunt. The pressure gradient was monitored during injections into the inferior vena cava (five patients). The pattern of the pressure gradient remained unchanged, although peak pressures in both atria rose a maximum of 2 mm in three patients. Although there was no significant change in gradient or heart rate during the period of cineangiography being evaluated, a temporary augmentation of heart rate and a gradient pattern change were noted 15 to 20 sec later.

3. The correlation of the time of onset and direction of flow across the atrial defect and the instantaneous pressure difference between the two atria was achieved by using the electrocardiogram as the common time base. Except in the instances described above, the atrial
Figure 1

Pressure-flow relationships of the left-to-right shunt in atrial septal defects. The graphic recording shows the instantaneous pressure differences across the atrial defects simultaneously recorded in the electrocardiogram (top tracing), the right and left atrial pressures (middle tracing), and the instantaneous pressure difference across the defect (lower tracing). These tracings were characteristic of 24 of the 26 patients studied. Note that the major gradient favors the left-to-right shunt during an interval which spans the latter portion of ventricular systole and early diastole with a secondary increase during atrial contraction.

The lower portion of the figure shows the left-to-right shunt as depicted on the cine frames following injection of contrast material into a left pulmonary vein.

Pressures and their pressure difference were recorded just prior to the injection of contrast material. The selected cine frames were related to their cine spikes as obtained from the photocell device described above, and their time relationship to the electrocardiogram was noted. These points on the electrocardiogram were in turn related to the recorded pressure difference and its simultaneously recorded electrocardiogram after allowing for the 5 to 10-msec delay in the catheter response. Thus, each cine frame could be referenced in real time to the pressure gradient (fig. 1). Care was taken in this correlation to ensure that the heart rate remained constant by measurement of the R-R intervals. The correlation was concerned mainly with the
Atrial Pressure-Flow Dynamics

Data recorded during biplane cineangiography. All data were simultaneously recorded photographically. (A) At a slow paper speed. (B) On magnetic tape for playback with expansion of the time scale.

Portion A shows, from top to bottom, the electrocardiogram, the outputs of the photocell timing device for the AP and lateral cine units, and the right atrial pressure.

Portion B shows the boxed-in area in (A) replayed from magnetic tape with time expansion. Note the 60/sec individual cine spikes of the photocell timing device which could be accurately related to the electrocardiogram and pressure curves. The arrow indicates the onset of injection.

timing of the onset of a pressure gradient favoring either atrium and the onset of flow across the defect in the direction suggested by such a gradient.

Results

Hemodynamic data on the 26 patients revealed the average systemic flow to be 3.8 L/min/m² (range, 3.1 to 4.5) with an average pulmonary flow of 8.5 L/min/m² (range, 5.7 to 12.0). The average left-to-right shunt was 65% (range, 59 to 74%) of total pulmonary blood flow. The average mean left atrial pressure was 5.8 mm Hg (range, 4 to 8 mm Hg) compared to the right atrial value of 5.1 mm Hg (range, 3 to 8 mm Hg). Simultaneously recorded left and right ventricular pressures showed an average peak systolic value of 112 mm Hg (range, 95 to 120 mm Hg) and 34.5 mm Hg (range, 25 to 45 mm Hg), respectively. The left ventricular end-diastolic pressure averaged 10 mm Hg (range, 8 to 11 mm Hg) and the right ventricular values averaged 6 mm Hg (range, 3 to 8 mm Hg).

In correlating the instantaneous pressure differences across the defect with the direction of flow as visualized by cineangiography, a time lag was found between these two parameters. The onset of flow in either direction across the defect occurred 50 to 75 msec after the onset of a gradient (zero pressure difference crossing) favoring the flow.* The cardiac rate varied between 90 and 130 beats/min, and the lag periods were shorter with faster heart rates and tended to be longer

*The onset of flow is defined in this study as the time when contrast media could be first visualized as crossing the defect. Since a finite period of time is required for the concentration of the media to increase to become visible by the cine method, this may have contributed significantly to the time lag between the onset of a pressure gradient and appearance of flow across the defect.
with rates that were slower. However, allowing for the time lag, the correlation between the direction of the pressure gradient and actual flow across the defect was consistent (vide infra).

**Left-to-Right Shunt**

To delineate the pressure gradients and flow patterns across the atrial defect during various intervals of the cardiac cycle, nomenclature problems related to the definition of systole and diastole immediately become apparent. Because the events of the ventricles and atria are asynchronous, we have chosen for this study to define systole in reference to the left ventricular (LV) pulse to include the time interval from the onset of the pressure rise until the time that the LV pressure has fallen below that of the left atrium (approximately the peak of the left atrial v wave). Diastole is therefore defined arbitrarily for this study as the time beginning with the peak of the left atrial v wave until the onset of LV contraction (approximately onset of the c wave of the left atrial pulse). In patients with atrial defects, the peak of the left atrial v wave was found to occur during the interval which separates the aortic and pulmonary component of the second heart sound. Thus, for the phonocardiographer, the definition used for systole is that time from the onset of the LV pressure rise to the interval of the split second heart sound. The definition of systole and diastole as used here is consistent with the original studies of Wiggers.9

A consistent pressure gradient pattern was found throughout the cardiac cycle (fig. 1). The most prominent left-to-right gradient developed during the latter half of systole with the most prominent gradient occurring approximately at the time of the peak of the left atrial v wave. The gradient dropped rapidly during early diastole and was moderately augmented during atrial contraction. Review of the cineangiocardiographic data in motion indicated a pulsatile flow across the defect with left-to-right shunting which appeared most prominent during the two intervals of the increased left-to-right gradient. The studies in motion further suggested that the major shunt occurred during the interval encompassed by the gradient which extended over the latter portion of systole and early diastole. During ventricular systole, the left-to-right shunt was associated with the left atrial pressure increasing more rapidly than that of the right with accentuation of the left-to-right gradient. Following the opening of the atrioventricular (A-V) valves, the rapid diminution of the left-to-right gradient was due primarily to the more rapid fall in left atrial pressure as compared to the right. This was associated with a decreasing left-to-right gradient and flow as diastole continued; however, atrial contraction was associated with augmentation of the left-to-right gradient and shunt due to the greater rise in the left atrial pressure as compared to that of the right.

**Right-to-Left Shunt**

The pressure-flow relationships of the right-to-left shunt across the atrial defect found in 24 of the 26 patients are illustrated in figure 3. Review of the cineangiocardiograms revealed that all patients had a transient right-to-left shunt. The timing of this transient shunt and right-to-left pressure gradient across the defect occurred during terminal QRS at a time coincident with the onset of left ventricular contraction. Following atrial contraction, the atrial pressures tended to equilibrate and with the onset of ventricular contraction, there was a characteristic "double-bump" gradient with flow in a right-to-left direction. This transient reversed gradient lasted from 80 to 140 msec and was immediately followed by a predominant left atrial pressure with a gradually increasing left-to-right pressure gradient as ventricular systole continued. The pressures of the two atria tended to approximate during early diastole (at the end of the y descent), and in two patients there was a transient right-to-left gradient at this time although no right-to-left shunt was demonstrable.
Small right-to-left shunt coincident with the onset of ventricular contraction. All patients demonstrated a minute right-to-left shunt with the onset of ventricular contraction. The pressure tracings shown are the same as those in figure 2. There was a characteristic "double-bump" gradient curve favoring the right atrium. The cine frames depicting the small right-to-left shunt (arrow) are shown with their time relationship to the transient right-to-left gradient.

All patients with the typical pressure gradient as was discussed failed to indicate a right-to-left shunt by peripherally recorded dye-dilution curves. The right-to-left shunt demonstrated by cineangiocardiology occurred with the onset of left ventricular contraction. This would result in closure of the mitral valve and failure of the shunted blood to enter the left ventricle. The tendency, however, was for the right-to-left shunt to occur at two phases; that is, at the onset of left ventricular contraction and during the period of early diastole (rapid ventricular filling phase). This suggested that the detection of systemic right-to-left shunts by peripherally recorded dye-dilution curves in these patients...
Effect of heart rate on the detection of systemic right-to-left shunting by peripheral arterial dye-dilution curves. Indocyanine green was injected at the inferior vena cava-right atrial junction while sampling was from the femoral artery.

(A) No right-to-left shunt was detected with a heart rate of 118 beats/min. (B) Dye curves repeated 20 min later following spontaneous slowing of the heart rate to 80 beats/min demonstrated the presence of a small right-to-left shunt.

The boxed-in areas of the electrocardiogram recorded during inscription of the dye curves were replayed at fast speed (top). Note the increase in the T-P interval indicating the prolonged diastolic period at the slower heart rate (see text).

should be enhanced by relatively slow heart rates which provide a more prolonged period of diastasis; thereby, a right-to-left gradient and shunt would develop during left ventricular filling. In one child, an initial arterial dye curve did not indicate a right-to-left systemic shunt with a ventricular rate of 118/min. Twenty minutes later, the heart rate slowed to 80 beats/min and the peripheral dye curve became positive for the right-to-left shunt (fig. 4). In another patient, a systemic right-to-left shunt was demonstrated in the presence of a heart rate over 100 beats/min. The pressure gradient studies in this child were atypical in that during the latter period of ventricular systole left and right atrial pressures equilibrated; with the onset of y descent, the left atrial pressure fell more rapidly than the right, producing a right-to-left gradient with the shunt occurring across the defect during the y descent of the atrial pulse at the time of rapid filling of the left ventricle as the A-V valves opened.
Figure 5

Effect of sustained positive pressure insufflation on pressure difference across defect. From top to bottom are shown the intrathoracic pressure, the electrocardiogram, the instantaneous atrial pressure difference, and the simultaneously recorded right and left atrial pressures.

During phasic changes in intrathoracic pressure, the left-to-right gradient was accentuated during periods of increasing pressure and diminished during periods of decreasing intrathoracic pressure. During the sustained positive pressure maneuver, there was a transient initial increase in the left-to-right gradient; this was followed by sustained reduction as the maneuver continued. At the completion of the maneuver, accentuation and overshoot of the left-to-right gradient occurred with immediate fall to the pre-maneuver level.

Effects of Respiration

The effects of changing intrathoracic pressure were studied under controlled respiratory states of apnea, intermittent positive pressure breathing, and sustained positive pressure insufflation. Spontaneous breathing was not evaluated since the children were under light anesthesia. With phasic changes in intrathoracic pressure (intermittent positive pressure breathing), the left-to-right gradient was accentuated during periods of increasing intrathoracic pressure and was diminished during periods of decreasing intrathoracic pressure. During sustained positive pressure insufflation (fig. 5), there was a transient initial increase in the left-to-right gradient; however, after 2 sec this was reduced, and this shift was maintained. Immediately upon release of the positive pressure, there was accentuation and overshoot of the left-to-right gradient with immediate fall to the pre-maneuver level. In summary, with phasic changes in intrathoracic pressure, the left-to-right gradient was accentuated as intrathoracic pressure increased and was diminished (or the right-to-left gradient became more prominent) during decreasing intrathoracic pressure; with sustained increased intrathoracic pressure, although the gradient remained predominantly left-to-right, the entire curve shifted toward the right.

Discussion

The nature of shunting of blood across secundum atrial defects has been the object of discussion and investigation for many years. Initially, Uhley\textsuperscript{10} suggested that the left-to-right shunt was related to the more cephalad position of the left atrium as compared to the right, thus implicating a gravitational factor as being the major mechanism.
This, however, was not consistent with the work of Brannon and associates\textsuperscript{11} whose work suggested that the relative resistance to filling of the ventricles was the main factor. Their conclusions were in agreement with Hull\textsuperscript{12} who considered that this resistance was due to the anatomy of the inflow tract of the ventricles and their respective valves. Nadas\textsuperscript{13} suggested that flow through the defect probably occurs throughout the entire cardiac cycle; whereas the work of Dexter\textsuperscript{14} indicated that the left-to-right shunt occurred mainly in diastole.

Other investigators have suggested that elucidation of shunting mechanisms in secundum atrial defects would be achieved only after simultaneous right and left atrial pressures and their differences were recorded.\textsuperscript{1,15} Of major concern in such studies is the small magnitude of the phasic pressure differences between the two atria in this situation together with the possibility that recording techniques may produce artifactual pressure differences. Although these are problems, the work of Shaffer, and associates\textsuperscript{16} and Courand and co-workers\textsuperscript{15} showed consistent phasic differences in the left and right atrial pressure curves in secundum atrial defect patients; however, the pressures were not recorded simultaneously. Furthermore, the present study indicates the ability to measure small pressure differences in this situation since there was excellent agreement between the pressure gradients recorded before and after reversal of the entire catheter recording systems.

The experimental design of this study for determination of the direction and timing of flow across the defect involves the presently unanswered question concerning the effect of injection of contrast media upon atrial dynamics in atrial defects. Whereas our initial results indicated excellent agreement between the pressure gradient pattern and the shunt visualized cineangiographically, in most patients the pressure gradient recordings were followed by cineangiography (that is, pressure and flow were evaluated asynchronously). Thereafter, in several patients the pressure gradient was recorded simultaneously with contrast injections into the pulmonary artery and pulmonary veins. The results of these injections showed no change in the gradient pattern during the first few seconds after injection (the time of study of flow), although peak pressures in both atria rose 2 mm in three patients. These checks indicated that the correlation of pressure and flow dynamics, although containing some inherent error, accurately depicted the atrial pressure differences accounting for the timing and direction of shunting across the defect. It is also pertinent to note that the visualization of shunting is more apparent when the cines are reviewed in motion. The generally poor reproduction of still pictures requires the reader to depend greatly on the author's interpretation.

Allowing for the time lag, these studies showed an excellent and consistent correlation between the direction of the pressure gradient and the direction of the shunt across the defect. As discussed by McDonald,\textsuperscript{17} in a pulsating system such as the aorta, where there is no orifice, the pressure gradient consists of a large inertial component and a smaller resistive component. In this situation, the pressure gradient can be considered to consist of components which respond to the rate of change of velocity as well as directly to velocity. Therefore, the finding of a negative pressure gradient will not necessarily determine the direction of flow at a specific instant of time because flow will lag behind the pressure gradient. In three patients, a transient right-to-left gradient occurred at the end of the “y” descent without concomitant flow in this direction. This can be accounted for by deceleration of the left-to-right shunt during this brief interval, without actual reversal of flow.

**Shunting Dynamics**

The present study indicated that the left-to-right shunt across the atrial defect occurred as a pulsatile flow associated with a left-to-right gradient over the interval of the latter half of ventricular systole and the first portion
of diastole with a second accentuation during atrial systole. Quantitation of flow across the defect in various portions of the cardiac cycle was not performed; however, the flow depicted cineangiographically suggested that the major shunt across the defect occurred in association with the prolonged gradient extending over late systole and early diastole.

Wennevold has described a "diastolic" murmur which can be recorded by intracardiac phonocardiography in the right atrium in many patients with atrial defects. Interestingly, the early diastolic murmur described in his report appeared to have its onset during late ventricular systole (as defined for this report) with extension into diastole. Thus, the timing of the right atrial murmur in his study coincided with the timing of the predominant left-to-right gradient which extended during the latter portion of systole into early diastole. He also described a late diastolic murmur in the right atrium which appeared to coincide in timing with the left-to-right gradient found in this study during atrial contraction. This is of interest since such murmurs detectable in the atrium, but not apparent on the body surface, may thus be related to the development of small pressure gradients across the defect. Usher also has demonstrated by phonocardiography that right atrial murmurs are inconstant but they may extend from midsystole into diastole. He found that these murmurs intensified with expiration and diminished with inspiration. This correlates with the findings of this study in that the left-to-right gradient increased during intervals of increasing intrathoracic pressure and diminished during periods of decreasing intrathoracic pressure.

The results of this study are in general agreement with those of Gamble and associates who continuously recorded right atrial blood oxygen saturation with fiberoptic catheter techniques. Their studies indicated that the predominant left-to-right shunt occurred during ventricular systole; however, they found three distinct left-to-right shunt peaks throughout the cardiac cycle. The present study indicated that flow across the defect occurred at a two phase phenomenon in all patients. This discrepancy with the work of Gamble and associates is unexplained and may possibly be related to the influence of systemic venous inflow affecting the fiberoptic results.

A transient and minute right-to-left shunt was consistently noted to occur coincident with the onset of left ventricular contraction. This occurred at a time when the A-V valves closed and prevented the entry of right atrial

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**Figure 6**

Intracardiac pressure dynamics in secondum atrial septal defects.

The tracings were obtained with simultaneous monitoring of right and left ventricular pressures by means of Statham SF-1 pressure-tipped transducer catheters. The catheters were subsequently withdrawn to record both atrial pressures. There was no change in rate (R-R interval remained constant). All data were recorded simultaneously with the lead II electrocardiogram and the phonocardiogram in the second left interspace. A composite was made by direct overlay tracings to produce the time aligned data as indicated.

The predominant left-to-right gradient occurred over an interval extending from midsystolic systole into early diastole. The peak of the left atrial v wave was coincident with the interval of the second sound. The fluctuations in left atrial pressure can be seen to be more prominent than those of the right atrium. The transient right-to-left gradient occurred coincident with the onset of ventricular contraction.
shunted blood into the left ventricle. All patients demonstrated a more prominent fall in left atrial pressure as compared to right atrial pressure at this time with the development of a transient gradient favoring right-to-left flow (fig. 3). Wiggers suggested that the movement of the base of the ventricles produces greater fluctuations in left atrial pressure as compared to the right. This effect probably accounts for the transient right-to-left shunt following the onset of ventricular contraction.

The dynamic pressure-flow relationships between the atria and the timing of ventricular events are illustrated in figure 6. These data were obtained with SF-1 pressure transducer-tipped catheters placed simultaneously in the left and right ventricles and subsequently they were withdrawn to the respective atria. All data were recorded simultaneously with the electrocardiogram; the phonocardiogram was recorded in the second left interspace. The timing of the phonocardiogram in relationship to the intracardiac pressures indicates that the peak of the left atrial v wave occurs between the aortic and pulmonic components of the second sound and that the left-to-right gradient extending over late ventricular systole and early diastole shows a peak during the second sound.

The changing intracardiac pressures as related to the timing of the shunt give strong support to the theories of Courand and co-workers concerning the mechanisms of the left-to-right shunt. Of considerable importance was the finding that a major component of the left-to-right gradient and shunt occurred during the latter half of ventricular systole when both A-V valves were closed. The peak left-to-right pressure gradient occurred at the apex of the left atrial v wave, as found in normal adults by Braunwald, and associates. As suggested by Courand and associates, the dynamics of shunting have to be related to the inherently distinct dynamic conditions of both atria. They suggested that the factors influencing these conditions include the anatomic differences between (1) the two atria, the left atrium having a thicker wall than the right, (2) the venous reservoirs, the pulmonary veins being shorter and their diameter smaller than the superior and inferior venae cavae, and (3) the effect of the ventricles, the muscular development of the left ventricle being much greater than that of the right. These anatomic differences result in the left atrium being less deformable than the right; its venous reservoir has a smaller capacity, and the effects of muscular activity of the left ventricle upon the volume and tension of the left atrium are more pronounced than similar activity of the right ventricle upon volume and tension in the right atrium. Although these theories are supported by the pressure-flow data obtained in this study, the problem as to how the

![Figure 7](http://circ.ahajournals.org/)

**Figure 7**

First time derivative of atrial pressures. The data were calculated by a digital computer from the tape-recorded right and left atrial pressures shown in figure 2. The calculated values were fed to a Calcomp plotter which displayed the data in the above graphic form. (A) The left (LA) and right (RA) atrial pressures were measured by the computer at 1-msec intervals and reconstructed as shown. (B) First time derivative of the left (LA) and right (RA) atrial pressure curves. Note the greater fluctuation in the derivative of the left as compared to the right atrial pulse. (C) Instantaneous pressure gradient.

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shunt is initiated following birth remains to be clarified.

To delineate more clearly the rate of pressure change of the two atria, the originally recorded data on magnetic tape were transcribed by an analog-to-digital converter, and analyzed by an IBM 7072 digital computer. These methods have been previously reported. In summary, the digital computer calculated the continuous pressure difference between the two atria as well as determining their rates of pressure change (first time derivative of the atrial pressure curve). The final output was fed to a Calcomp plotter which graphically demonstrated the simultaneously recorded atrial pressures, the first derivative of the atrial pressures, and the pressure difference. A typical result is shown in figure 7, which graphically demonstrates the tendency of the left atrial pressure curve to fluctuate more than that of the right. This can be accounted for by the low compliance of the left atrium with its small venous reservoir as compared to the high compliance to the right atrium with its large venous reservoir. Therefore, any changes in position of the ventricular base and the muscle tone of the atria would cause greater fluctuations in pressure in the left than in the right atrium.

Effects of Respiration

The effects of respiration upon the pressure gradient across the defect showed that with phasic changes in intrathoracic pressure, the left-to-right gradient increased during periods of increasing intrathoracic pressure and decreased during periods of decreasing intrathoracic pressure. The mechanisms for these changes remain unexplained from the data obtained, since flow determinations were not conducted relative to pulmonary and systemic venous inflow through the respiratory cycle. The pressure changes occurred in a direction which was consistent with the work of Kilburn and Sieker which indicated that systemic venous inflow to the right atrium was diminished during increased intrathoracic pressure. The reduction in the maximal pressure difference between the two atria and the shift of the gradient toward the right during sustained positive pressure insufflation may primarily be related to the decreased central blood volume that occurs with sustained increased intrathoracic pressure. Although the effects of respiration were consistent, the mechanisms responsible for the pressure gradient changes remain to be clarified by methods which determine simultaneously the pressure difference and blood flow into the atria in patients with atrial defect.

Acknowledgment

The authors would like to express their appreciation to Dr. Joseph C. Greenfield for his many helpful suggestions during the course of this study; to Dr. L. Jerome Krovetz of the Department of Pediatrics, University of Florida School of Medicine, Gainesville, Florida, for his most helpful comments which led to the final clarification of the time lag between the gradient and flow across the atrial septal defect; and, finally, to Miss Eugenia E. Cole for her most valuable technical assistance.

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Correction

On page 985 (vol. 36, 1967) of the "Recommendations for Human Blood Pressure Determinations by Sphygmomanometers" it is stated "To measure blood pressure by the flush method, a suitable cuff is placed on the forearm or calf . . ." This is in error and should read "To measure blood pressure by the flush method, a suitable cuff is placed on the wrist or ankle. . . ."
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Circulation. 1968;37:476-488
doi: 10.1161/01.CIR.37.4.476

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