Dynamics of Interatrial Shunting in Children with Obstruction of the Tricuspid and Pulmonic Valves

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SUMMARY
The interatrial pressure-flow dynamics in patients with right-to-left shunting at the atrial level in the presence of right heart obstruction were studied. In tricuspid atresia most of the right-to-left gradient occurred during right atrial systole. This gradient, as well as the cineangiograms, indicated that almost all systemic venous return was transferred from the right to the left atrium through the interatrial communication during right atrial contraction. Cine studies also suggested that right atrial systole (1) contributed significantly to left ventricular filling and (2) produced regurgitant venous flow, especially into the hepatic veins.

In two patients with secundum atrial defect and associated marked pulmonic valve stenosis, bidirectional shunting at the atrial level was defined by pressure gradient and cine and dye-dilution curve technics. The right-to-left gradient and shunt occurred during ventricular diastole with accentuation of this gradient by atrial contraction; the left-to-right interatrial flow and gradient occurred during ventricular systole when both A-V valves were closed. These studies indicate that, in the presence of an interatrial communication, increasing degrees of right heart obstruction not only produce right-to-left shunting but (1) do so primarily by right-to-left flow across the interatrial communication during ventricular diastole and (2) with complete right atrial obstruction, right atrial contraction plays a dominant role in the transfer of systemic venous return to the left atrium.

Additional Indexing Words: Secundum atrial defect Pulmonic valve stenosis Sustained intrathoracic pressure Vigorous inspiration

The study of pressure-flow relationships across the atrial septum in secundum atrial defects has shown that the timing of the left-to-right shunt can be correlated with the changing interatrial pressure gradient across the atrial septum. However, little information is available concerning atrial dynamics in conditions which result in varying degrees of right-to-left atrial shunting secondary to right heart obstructive diseases, such as tricuspid atresia and severe pulmonic valve stenosis with atrial septal defect. This study was conducted to determine the timing and direction of the pressure gradient and right-to-left shunt across the atrial septum in a select group of patients with either complete obstruction of the tricuspid valve or increased resistance to right ventricular outflow (pulmonary stenosis). Of particular interest was the nature of the atrial pressure-flow dynamics in conditions in which the atrial defect or patent foramen ovale presented the only outlet for flow from the right atrium (tricuspid atresia) as compared to the situation when flow from the right

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atrium occurred both into the right ventricle and across the atrial septum (atrial septal defect with pulmonary stenosis).

**Methods**

Interatrial pressure-flow relationships across the defect were studied in 11 patients. Two children, aged 6 and 8 years, had severe valvular pulmonic stenosis (peak right ventricular pressure greater than that of the left) and a secundum atrial defect. The diagnoses were confirmed at surgery in both patients. The remaining patients had tricuspid atresia, type Ib according to the Keith classification (pulmonary hypoplasia and small ventricular septal defect). Their ages varied from 18 months to 5 years. Cardiac catheterization was carried out under light nitrous oxide anesthesia with the patient in a supine position. However, in one child with tricuspid atresia, sedation rather than light anesthesia was used; this provided the opportunity to transiently observe the effects of vigorous respiratory motion when she awoke and began to cry. All patients were documented to have a right-to-left shunt isolated at the atrial level as indicated by the presence of tricuspid atresia or a right-to-left shunt in the peripheral arterial dye-dilution curve following injection of indocyanine green (Cardio-Green) into the right atrium with no evidence of a right-to-left shunt following a similar injection into the right ventricle in the two patients with pulmonary stenosis. Systemic and pulmonary blood flows were calculated from blood-oxygen saturation data (Fick principle). Inspired air and blood oxygen content were measured with an Instrumentation Laboratory's 113 PO₂, P O₂, and pH meter. The inspired air was sampled intermittently to maintain the oxygen concentration between 20.5 and 21 vol%. In the group of patients having tricuspid atresia, heart rates varied from 150 to 180 beats/min, and arterial oxygen saturation values varied from 65 to 84%. In the two patients with secundum atrial defect and pulmonary stenosis, the pulmonary to systemic flow ratios were 1.5 or greater.

The methods employed for studying the pressure-flow relationships between the right and left atrium have been described in previous detail. These were designed to evaluate (1) the continuous pressure difference across the atrial septum, (2) the timing and direction of flow across the atrial defect,* and (3) the relationship of the pressure gradient and the direction and timing of flow between the two atria.

**Continuous Pressure Difference**

The continuous pressure difference was derived from the right and left atrial pressure curves with the following system: No. 6 or 7 side-holed catheters were connected to Statham P23Cb pressure transducers which were fed to Sanborn 350-1100 carrier preamplifiers. The catheters were matched for equal length, volume, and transmission time. The characteristics of the system approach the criteria for pressure gradient determination described by Greenfield and Fry. The outputs of the preamplifiers were fed to a Heathkit EC-1 analog computer to subtract the right from the left atrial pressure. The analog computer output (pressure difference) was recorded simultaneously with the atrial pressures and the electrocardiogram. To estimate the noise level in the pressure gradient curve in two patients, curves were recorded with the two catheter tips positioned together in the right atrium (fig. 1); the maximal peak-to-peak noise level was ± 1.5 to 2.0 mm Hg for rapidly changing pressures.

Prior to and after each recording, zero baseline conditions were measured in reference to the midchord position to insure that there were no baseline shifts. To rule out errors in the continuous pressure gradient, the positions of the atrial catheters were reversed and the recordings repeated. In each patient, similar gradients were obtained. All pressures were recorded just prior to the injection of contrast medium.

**Timing and Direction of Flow**

The timing and direction of flow across the defect were studied with biplane cineangiocardiology at a sampling rate of 60 frames/sec. Seventy-five per cent Hypaque (sodium and meglumine diatrizoate, 1 ml/kg) was injected into the inferior vena cava at the level of the inferior border of the liver or directly into the right atrium to study the right-to-left shunt across the defect. Left-to-right shunting was evaluated from injections into left atrium or, whenever possible, into a pulmonary vein. All injections were performed during apnea approximately 5 to 8 seconds after cessation of respiratory motion. To relate the shunt to the cardiac cycle, the individual cine frames were timed with the electrocardiogram by means of a special photocell device. All data were recorded graphically and simultaneously on magnetic tape for playback with expansion of the time scale.

Previous studies in patients with secundum atrial defects indicated that the pattern of the pressure gradient remained unchanged during the

*All patients were demonstrated by cineangiocardiology to have an interatrial septal communication; however, no anatomic distinction was made between a foramen ovale and secundum atrial defect except when this was possible at surgery in the patients with pulmonary stenosis and secundum atrial defect.
immediate filming interval following contrast medium injection, although peak pressures in both atria in some patients increased 2 mm Hg. Two patients with tricuspid atresia in the present study underwent similar studies, and they likewise demonstrated no change in the pattern of the pressure gradient. To obviate respiratory effects, all cineangiocardiograms were performed during apnea.

**Correlation of Onset and Direction of Flow**

Correlation of the onset and direction of flow across the defect with the pressure gradient was done by using the electrocardiogram as a common time base. After previously determining the catheter response delay time (5 to 10 msec) the individual cine frames were related to the instantaneous pressure gradient. In this correlation, care was taken to measure beats with constant R-R intervals to insure that the heart rate remained constant.

**Results**

**Tricuspid Atresia**

The interatrial pressure relationships and timing of the atrial right-to-left shunt were similar in all of the nine patients, with only minor variations in the timing of the shunt. Typical curves of the continuous right and left atrial pressures and the continuous pressure gradient are shown in figure 2. The right atrial a wave was elevated in all patients (peak RA pressure—a wave—ranged from 11 to 15 mm Hg), and it was considerably longer in duration than that of the left atrium. Right atrial c waves were absent.

The direction of the gradient was almost entirely in a right-to-left direction. There were small (1 to 2 mm Hg) fluctuating gradients in favor of either atrium during ventricular systole. Immediately thereafter the right-to-left gradient began to increase slightly during the y descent of the left atrial v wave. The onset of right atrial contraction occurred shortly thereafter, primarily due to the tachycardia. Atrial systole accounted almost entirely for the right-to-left gradient which reached peak values of 9 to 13 mm Hg during apnea.

*Estimate of noise level in pressure gradient curves. Two matched no. 7 side-hole catheters were positioned with closely apposed tips in the right atrium of a 2-year-old child with tricuspid atresia. The pressure curves recorded from the two catheters (lower trace) appear identical; however, the pressure gradient curve shows rapid undulations indicating a maximum peak-to-peak noise level of ± 1.5 to 2.0 mm Hg. Lead II of the electrocardiogram is shown at top.*
Interatrial pressure-flow relationships in tricuspid atresia. These data were recorded in a 2-year-old child with tricuspid atresia, small ventricular septal defect, and small outflow tract of the right ventricle with diminished pulmonary blood flow (type Ib). The simultaneous right (RA) and left (LA) atrial pressures are shown with a lead II of the ECG (top) and the continuous pressure difference (below). A downward deflection of the pressure gradient curve indicates that right atrial pressure exceeds left atrial pressure. The cine frames are shown below with the connecting lines indicating time alignment with the pressure gradient. These data were typical of the patients with tricuspid atresia.

Note that the right-to-left gradient is primarily related to the prominent right atrial a wave, that is, atrial systole. Other consistent findings were the considerably larger right atrial a wave as compared to that of the left, and the absence of a right atrial c wave.

Note that the cine frames indicate sequentially (1) minimal flow across the septal communication prior to atrial systole, (2) marked augmentation of right-to-left flow during the right atrial a wave, and (3) filling of the left ventricle with contrast material transferred to the left heart during atrial contraction. Also, right atrial contraction produced regurgitant flow into the vena cava, especially to the hepatic veins via the inferior vena cava (indicated by arrow).
As noted, throughout the remainder of the cardiac cycle (during the interval of atrial diastole during which ventricular contraction occurred) the atrial pressures equilibrated with minor transient bidirectional fluctuations.

Biplane cineangiocardiograms revealed that the timing of the right-to-left shunt across the atrial septum was best considered in relation to the overall abnormal right atrial flow pattern. The venous inflow into the right atrium occurred in a to-and-fro manner. During atrial systole the right atrial output consisted of two components: (1) blood flow across the atrial septal defect into the left atrium and (2) retrograde blood flow into the vena cava (fig. 2). The right atrial systolic venous regurgitant fraction especially involved considerable distention of the hepatic veins. Immediately following the completion of atrial systole, the hepatic veins emptied rapidly with inflow into the right atrium. In four patients there appeared to be selective flow of the inferior vena cava inflow posteriorly along the atrial septum. When the contrast material reached the level of the atrial defect, the right-to-left shunt began during the y descent of the left atrial v wave; this was accentuated within 50 to 100 msec from the onset of atrial contraction. In the remaining five patients, the right-to-left shunt occurred entirely during right atrial systole (right atrial a wave); during atrial diastole, the rapid atrial inflow surge of venous blood (contrast medium) from the hepatic veins also appeared to flow preferentially in a posterior manner along the atrial septum, but no flow across the septum occurred until right atrial systole began.

Injections into the pulmonary vein revealed

\[ \text{Figure 3} \]

*Effect of vigorous crying on the interatrial pressure gradient in tricuspid atresia. These data were recorded when the 2-year-old patient, whose data are shown in figure 2, awakened and began to cry. Marked increase in the right-to-left interatrial gradient occurred with the peak of the rapid forced inspiration phase of crying and this gradient remained primarily confined to the period of atrial systole. Also, the more forceful inspiratory gasps (noted from the marked swings of negative pressure in the atrial pressure curves) produced increases up to 18 mm Hg in the right-to-left gradient, whereas less vigorous inspiratory efforts caused only mild accentuation in the pressure difference between the atria.*

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small whiffs of contrast medium across the septal defect from the left atrium; the timing of this small left-to-right shunt was such that it never occurred during atrial systole, and it may have been related to the position of the catheter across the interatrial communication. Thus, only minimal amounts of contrast medium could be visualized to cross the atrial septum in either direction during intervals of the cardiac cycle when the atria were in a relaxed state; the major discernible flow occurred in a right-to-left direction throughout the period of the quite prominent right atrial a wave. An additional feature of the right-to-left shunt was depicted from the AP cine projection which demonstrated that the venous blood transferred to the left atrium during right atrial systole seemed to contribute significantly to left ventricular filling just prior to the onset of ventricular contraction (fig. 2).

The influence of vigorous crying on the interatrial pressure gradient was observed during the course of the catheterization in the child with tricuspid atresia whose data are discussed above. During the forced expiratory phase (crying phase), the right-to-left peak gradient gradually diminished during atrial systole (fig. 3). Coincident with vigorous inspiratory gasps, the right-to-left gradient increased, and the maximal gradient occurred at peak inspiration. This resulted in interatrial pressure gradients reaching a level as high as 18 mm Hg.

The effects of sustained increased intrathoracic pressure were evaluated in three children with tricuspid atresia. The maneuver was repeated in each patient on several occasions with reproducible results. This produced three sequential changes (fig. 4): (1) Immediately following the onset of sustained increase in intrathoracic pressure there was a transient and marked decrease in the right-to-left gradient during atrial systole with an associated shift of the entire pressure gradient in favor of the left atrium. (2) As increased intrathoracic pressure was maintained, the duration of the right atrial systolic

![Graph showing intrathoracic pressure on interatrial pressure gradient in tricuspid atresia](image-url)

**Figure 4**

Effect of sustained increased intrathoracic pressure on interatrial pressure gradient in tricuspid atresia. These data were recorded in a 3-year-old child with tricuspid atresia. During resting respiration the right atrial (RA) pressure continuously exceeded that of the left (LA). With the onset of sustained increased intrathoracic pressure, there was a transient decrease in the right-to-left gradient which quickly returned to near base-line levels. However, as the maneuver continued, there was a slight shift toward an increasing left-to-right gradient with a reduction in duration of the prominent right atrial systolic right-to-left gradient. Upon sudden release of the increased intrathoracic pressure, there was rapid resumption of the predominant right-to-left gradient with return to base-line duration of the right-to-left systolic gradient.
right-to-left gradient was shortened while the peak values returned to the original apneic level. (3) Immediately following termination of the sustained increased intrathoracic pressure, there was a rapid increase in the duration of the right atrial systolic right-to-left gradient to control levels.

Secundum Atrial Defect with Severe Valvular Pulmonic Stenosis

Both of these children, aged 6 and 8 years, had secundum atrial defects; the diameters of the defects were measured at surgery to be 2.5 and 3.0 cm, respectively. Additionally, valvular pulmonic stenosis was confirmed and

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**Figure 5**

*Interatrial pressure-flow relationships in atrial septal defect associated with marked pulmonary stenosis. These data were recorded in a 6-year-old child who was confirmed at surgery to have a secundum atrial defect (diameter 2.5 cm) and valvular pulmonic stenosis (RV peak systolic pressure was 100 mm Hg and RV end-diastolic pressure was 9 mm Hg). A. Arterial dye-dilution curves document the presence of bidirectional interatrial shunts by injections into the left pulmonary vein (I.S.: Lt. PV) and at the junction of the inferior vena cava and right atrium (I.S.: IVC-RA). B. The simultaneous right (RA) and left atrial (LA) pressure curves were overdrawn, along with the continuous pressure gradient (middle) and lead II of the ECG (top) to illustrate the phasic atrial pressure changes which produce the biphasic pressure gradients to account for the bidirectional interatrial shunting. Note the plateau-type, 2 to 3 mm Hg, left-to-right gradient throughout ventricular systole and the right-to-left gradient during atrial contraction.*
corrected. Preoperative right ventricular peak systolic pressures were 100 and 125 mm Hg. There was no associated ventricular defect in either patient. The interatrial pressure gradient, cineangiocardograms, and arterial dye-dilution curves were similar in both patients.

Figure 5 shows the interatrial pressure relationships (below), which were measured before and after recording the arterial dye-dilution curves (above). The indicator-dilution curves documented the presence of bidirectional shunting at the atrial level. The pressure gradients which accounted for the bidirectional shunting demonstrated phasic predominance of either atrium throughout the cardiac cycle. A right-to-left gradient was present during ventricular diastole; it began during the y descent of the left atrial v wave coincident with a more rapid fall in left atrial pressure as compared to that of the right. This right-to-left gradient was accentuated to its peak value during atrial systole. The gradient which accounted for the left-to-right shunt across the atrial defect occurred throughout ventricular systole as a rather constant plateau-type, 2 to 3 mm Hg, left-to-right gradient. The direction and timing of the interatrial bidirectional shunts were also seen by cineangiocardiography to coincide with the pressure gradient curves with the right-to-left interatrial shunt visible only during ventricular diastole.

Discussion
Consideration of the Methods
An initial comment is in order concerning the potential limitations of the methodology used to measure interatrial pressure differences and to estimate the timing of the flow by cineangiocardiographic techniques.

Fluid-filled catheters have an inherent pulse transmission time lag in contrast to the use of transducer-tipped catheters; however, by appropriate matching of the catheters and, by recording the pressure gradient after alternating the catheters in each atrium, the similar gradients provide good assurance for the absence of large artifactual components in the curves. Additionally, the opportunity to record simultaneous pressures with the catheter tips juxtaposed within the right atrium suggested that the interatrial gradients discussed were considerably above the noise range.

The interpretation of flow with the use of contrast medium presents a more formidable problem, especially, since the injection of contrast medium may alter the pressure-volume characteristics of the atria. In two children with tricuspid atresia, both atrial pressures were monitored during injection of contrast medium into the upper inferior vena cava. This produced no change in the timing relationships of the pressure gradient although peak right atrial systolic pressure increased 2 mm Hg for three beats. Thus, for these beats a small fraction of the atrial systolic right-to-left gradient was due to the injection of contrast medium. Interestingly, the timing of onset of a jet type of flow across the foramen ovale began during the right atrial a wave in these patients. Thus, this would seem to allow a legitimate interpretation in the patients with tricuspid atresia that the major contribution of the right-to-left shunt occurred during right atrial contraction.

All of the patients with tricuspid atresia had heart rates in the range of 150 to 180 beats/min; this precluded an evaluation of pressure-flow relationships during a prolonged interval of diastasis (onset of y descent of the left atrial v wave to onset of atrial contraction).

The major unknown factor in the tricuspid atresia patients was the size of the interatrial communication. Thus, we have elected to classify the interatrial communication as a foramen ovale, as contrasted to a larger secundum atrial defect, with some justification for this based on the large interatrial gradients generated during atrial systole. None of these patients were treated by atrial septostomy or septectomy; all subsequently were subjected to surgical therapy with systemic-to-pulmonary artery shunts.

Evaluation of Atrial Pressure-Flow Dynamics
The right atrial pressure curves in tricuspid atresia were characterized by a very prominent a wave and by the absence of the c component in tricuspid atresia. The absence of
the c component can be accounted for by the complete obstruction of the tricuspid valve opening. Also, at these heart rates, the pattern of the right-to-left interatrial pressure gradient was constant among the patients with tricuspid atresia despite variability in pulmonary-to-systemic blood flow ratios; in other words, arterial oxygen saturations varied from 65 to 84%. In these patients the outflow of blood from the right atrium required transfer of the total systemic venous return across the interatrial communication to the left atrium. The finding that almost all of the right-to-left pressure gradients, at least at rates above 150 beats/min, occurred during atrial systole is interesting since the cineangiocardiograms indicated that the transfer of systemic venous return to the left heart was primarily limited to right atrial systole. This suggests that right atrial contraction is a major determinant of systemic cardiac output in patients with tricuspid atresia and that rapid deterioration of systemic flow might result if these patients should develop atrial fibrillation.

The abnormal to-and-fro vena caval right atrial flow pattern, as depicted by cineangiocardiograms, was consistently seen in patients with tricuspid atresia. The right atrial systolic venous regurgitation appeared to occur preferentially into the hepatic venous radicles; indeed, the cines suggested that of the "total right atrial systolic output" more blood may possibly be ejected in a regurgitant manner into the systemic venous connections than is ejected across the atrial defect into the left atrium. Also, the pulsatile nature of the movement of contrast medium into and out of the hepatic veins suggested that they may rapidly empty into the right atrium due to recoil from the atrial systolic distention. Tafur and Guntheroth have shown in dogs that normally there is reversal of flow in the vena cava at the peak of the right atrial a wave. Wexler and co-workers demonstrated two peaks of forward flow throughout the cardiac cycle in the proximal vena cavae of two normal adult subjects. Thus, this normal phenomenon appears markedly enhanced with reversal of flow during atrial systole in the presence of tricuspid atresia.

Interpretation of the small left-to-right shunt across the foramen ovale during ventricular systole, as seen in AP cine projection following pulmonary vein injection of contrast medium in these patients, is most difficult to interpret as to whether such shunts occur without a catheter positioned across the interatrial communication. However, although such flow may have been due to the position of the catheter, the timing of this flow was limited to the interval of the cardiac cycle outside of atrial systole.

With complete obstruction of flow through the right heart and with the foramen ovale providing the only exit pathway, the influence of changing intrathoracic pressure was quite pronounced on the interatrial pressure dynamics. During crying, vigorous inspiratory gasps were associated with transient and marked increases in the right-to-left gradient during atrial systole. This can be accounted for by augmented inflow of blood into the right atrium associated with the sudden drop in intrathoracic pressure, while there would be only slight effect (decrease?) on left atrial inflow from the pulmonary veins in the presence of reduced pulmonary blood flow. Additionally, sustained increases in intrathoracic pressure were associated with a diminished right-to-left gradient; this was primarily related to a decrease in the duration of the right atrial a wave and can be accounted for by diminished venous inflow of blood into the right atrium. Continued diminished inflow into the right atrium also probably accounts for the gradual increase in left-to-right atrial diastolic gradient as the increase in intrathoracic pressure is maintained (fig. 4).

The two patients with a secundum atrial defect and severe valvular pulmonic stenosis present a situation which can be considered hemodynamically between that of a pure secundum atrial defect and complete right atrial obstruction. These two patients were shown to have bidirectional interatrial shunts with the use of right and left atrial injections.
of indocyanine dye and by cineangiocardiography. The right-to-left shunt was accounted for primarily by the predominant right-to-left gradient during ventricular diastole. This gradient was associated with a more rapid fall in left atrial pressure than that of the right during the y descent of the left atrial v wave; there was subsequent accentuation of the right-to-left gradient during atrial contraction. The left-to-right shunt was accounted for by the left-to-right interatrial gradient during ventricular systole. The explanation of the predominant left-to-right shunt during the diastolic phase of atrial activity, when both A-V valves are closed, calls for evaluation of the complex interrelationships of the inflow, the volume, and the compliance of the two atria and their venous connections. Although we have no data on atrial volume and compliance, both of these patients had calculated pulmonary-to-systemic flow ratios greater than 1.5. Thereby, the considerably greater magnitude of pulmonary venous return, as compared to systemic return, would accentuate the tendency for transfer of blood from the left to the right atrium across the defect during an interval when both A-V valves are closed and the atria are inactive.

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