Some immediate hemodynamic consequences of closure of atrial septal defects of the secundum type

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ABSTRACT The circumclusion method for surgical closure of atrial septal defects (ASDs) of the secundum type makes it possible, during surgery, to close and reopen the defect as desired. In each of 23 patients the following statistically significant pressure and flow changes were found when the ASD was closed: increasing mean pressures in the ascending aorta (from 74 to 87 mm Hg), left atrium (from 10 to 18 mm Hg), and right pulmonary artery (from 20 to 24 mm Hg); increasing mean flows in the ascending aorta (from 84 to 111 ml/min/kg); decreasing mean pressures in the right atrium (from 9.0 to 7.7 mm Hg); and decreasing mean flows in the right pulmonary artery (from 78 to 46 ml/min/kg). Surprisingly, no correlation between shunt size determined before and during surgery was found. However, in the calculation of the intraoperative shunt, several factors might have contributed to an erroneous result. In 17 patients a right heart catheterization was performed in the third to thirteenth postoperative month and the following statistically significant changes from the intraoperative results with closed ASD were found: The intraoperative mean pressure in the left atrium (18 mm Hg) decreased to 7.3 mm Hg after surgery (pulmonary wedge pressure), the pulmonary arterial pressure decreased from 23 to 13 mm Hg, and the right atrial pressure from 8.2 to 1.6 mm Hg.


LITTLE is known about the immediate hemodynamic consequences of surgical closure of atrial septal defects (ASDs) of the secundum type.

This operation is most often performed with the use of extracorporeal circulation. However, the closed method of circumclusion reported by Søndergård et al. is still used routinely at some centers. The method makes it possible to close and reopen the defect repeatedly as desired during surgery.

The purpose of our investigation was to measure the possible changes after circumclusion in the following: (1) heart rate, (2) the pressures in the right and left atria, right ventricle, right pulmonary artery, and ascending aorta, and (3) blood flow in the right pulmonary artery and ascending aorta. Furthermore, results were compared with those obtained from a postoperative right heart catheterization.

Material and methods

Measurements were obtained from 23 patients (pressure measurements in 21, flow measurements in 19). There were 13 male and 10 female subjects whose ages ranged from 4 to 68 years (median 11, quartiles 8 and 27). In all patients preoperative right heart catheterization was performed and the diagnosis of ASD of the secundum type was made. No preoperative measures were taken to evaluate status of the left heart, but only the three oldest patients had signs of heart decompensation and they received digitalis and diuretics. The patients were anesthetized with halothane/meperidine and were not atropinized at the time of measurement. Through a right-sided thoracotomy in the fifth intercostal space the pericardial cavity was opened extensively 1 cm posterior to the phrenic nerve in each patient. The technique of circumclusion is illustrated in figure 1. The clavage between the right and left atria was dissected as far as possible from the aortic root to above the coronary sinus. The surgeon inserted his left index finger into the right atrium through a purse-string suture and the type, size, and location of the defect was determined. A blunt probe bent in a suitable curve was then guided by the finger in the septal tissue along the lower edge of the defect until the tip appeared in the triangle of fat located between the right and left atria and the coronary sinus. A heavy suture was fastened to the probe tip and the probe was pulled back carrying the suture. The tension of the suture adequate to cause closure of the ASD was determined with the finger in situ and by gradually pulling tight and loosening the suture the defect could be closed and reopened as desired. By insertion of hypodermic needles in the right and left atria, right ventricle, right pulmonary artery, and ascending aorta and with the use of pressure transducers (Elema Schönander EMT 35) and pressure amplifiers (Elema Schönander EMT 311), pressures were recorded from each of these locations. With a step test, the damping ratio of the pressure-measuring system was found to be 0.56 and the natural resonant frequency 10.8 Hz. With an electromagnetic flowmeter (Nycotron type 372) and external flow probes blood flow was determined in the right
pulmonary artery and the ascending aorta. The middiastolic and end-diastolic niveau on the flow curve was taken as zero-point niveau² and its calculation was based on planimetry of at least 10 pulses (Haff planimeter type 317). In 13 of the 19 patients the same probe could be used to measure the flow in both of the above-mentioned vessels. The probes were calibrated in a flow model in vitro as described previously.³ The frequency response of this flowmeter is stated by the manufacturer to be flat up to 10 Hz.

Both flows and pressures were recorded on a paper ink writer (Elema Schönander M 81). Closing and reopening of the defect was repeated at least twice. A calculation of the shunt during surgery when the ASD was open was made by estimating the flow value from the ascending aorta as cardiac output of the left side and estimating twice the value from the right pulmonary artery as cardiac output of the right side (as the only available estimate).

No perioperative or postoperative complications were observed and all patients were discharged from the hospital in good health. In 17 of the 23 patients a right heart catheterization performed in the third to thirteenth postoperative month confirmed closure of the ASD. Pressure measurements from this catheterization were compared with those obtained during surgery when the ASD was closed.

Results

There was no change in heart rate after circumclusion. The heart rate with the ASD open ranged from 60 to 162 beats/min (median 103) and with the ASD closed it ranged from 60 to 179 beats/min (median 103).

A typical example of the measurements obtained is illustrated in figure 2. When the ASD was open, the pressures in the right and left atria were almost identical. Closure was followed by a marked increase in the pressure in the left atrium and a decrease in that in the right atrium. In the pulmonary artery the systolic pressure was almost the same as when the ASD was open, but the mean and diastolic pressures increased. A small decrease was observed in right ventricular pressure and the small pressure gradient across the pulmonic valve when the ASD was open diminished. In the ascending aorta a marked increase in the pressures as well as in
the pressure amplitude was observed to follow closure of the ASD.

In figures 3 to 7 the pressure results are illustrated. Changes were considered statistically significant at \( p < .01 \) (paired t test). In figure 3 the results from the pressure measurements in the ascending aorta are shown. Significant increases in systolic, diastolic, and mean pressures were observed. No significant changes were found in the right ventricle (figure 4), but significant increases in diastolic and mean pressures in the pulmonary artery were found to follow closure (figure 5). No significant change was seen in the systolic pressure (figure 5). Figure 6 shows the marked and significant increases in maximum, minimum, and mean pres-

FIGURE 2. An example of the pressure measurements. From top to bottom the simultaneous registrations of pressures in the left atrium, right atrium, right pulmonary artery, right ventricle, and ascending aorta. The ASD is open, closed, and reopened. At the ordinate is pressure (mm Hg) and at the abscissa time (sec).

FIGURE 3. Pressure measurements in the ascending aorta. The systolic, diastolic, and mean pressures are illustrated with the ASD open and closed. At the ordinate is the pressure (mm Hg) and on each of the six ordinates the mean pressure is labeled. At the bottom of each column the p value indicates statistical significance (\( p < .01 \) considered significant, t test, method of paired comparison).
pressures in the left atrium that were found to follow closure of the ASDs. In figure 7 the corresponding significant decreases in the right atrium are illustrated. It should be noted that "maximum pressure" most often equaled the a wave. However, with the ASD open, the v wave was equal to or exceeded the a wave in the left atria of nine patients and in the right atria of two patients. The corresponding figures when the ASD was closed were five and two.

Typical examples from the flow measurements in the ascending aorta and the pulmonary artery are seen in figures 8 and 9. An increase in the flow in the ascending aorta as well as a decrease in the flow in the right pulmonary artery were noted. In figure 10 the results from the flow measurements are illustrated.

The results from the pressure measurements (ASD open) were compared with the pressures determined before surgery at catheterization. By linear correlation analysis, statistically significant positive correlations were found between the preoperative and intraoperative mean pressures in the pulmonary artery (p < .001), right ventricle (p < .001), and right atrium (p < .05). There was no correlation between the mean pressures before and during surgery in the left atrium. The lines of regression and the corresponding correlation coefficients found were pulmonary artery: y = 0.26x + 15, r = .46; right ventricle: y = 0.39 + 9, r = .51; right atrium: y = 0.35x + 7, r = .26; left atrium: y = -0.03x + 10, r = -.04 (y = intraoperative mean pressure with open ASD; x = preoperative mean pressure).

Further analysis revealed a statistically significant (p < .001) positive correlation between the pressure increase in the mean pressures in the left atrium and the right pulmonary artery after occlusion of the defect. The line of regression was y = 0.63x + 6, r = .49 (x = left atrium; y = right pulmonary artery).

The estimate of the shunt during surgery was analyzed together with the shunt size determined before surgery obtained at catheterization. The intraoperative shunt varied from 0% to 194% (median 75, quartiles 45 and 113) of peripheral cardiac output and the preoperative shunt from 50% to 526% (median 159, quartiles 110 and 200) of peripheral cardiac output. Surprisingly, no statistically significant positive correlation between the two shunt values was found, either when data from all the patients were analyzed or when those from children and adults (<12 years/>12 years) were analyzed separately. The line of regression
for all the patients was \( y = 0.03x + 77, \ r = 0.06 \) (\( y = \) peroperative shunt; \( x = \) preoperative shunt).

It should be noted that figures 3 to 7 and 10 illustrate data obtained after only one closure of the ASD. Opening and closing of the ASD was always repeated and pressure and flow values consistently reverted to the same levels.

In figures 11 to 14 pressure measurements from the postoperative heart catheterization are compared with the corresponding pressure measurements made during surgery when the ASD was closed (the postoperative pulmonary arterial wedge pressure is considered equivalent to the intraoperative left atrial pressure). Statistically significant decreases were observed in systolic, diastolic, and mean pressures in the left atrium/pulmonary arterial wedge, pulmonary artery, and right atrium. In the right ventricle the systolic and diastolic pressures decreased significantly as well.

**Discussion**

Although closure of ASDs of the secundum type is a routine operation at most thoracic surgical centers, reports of pressure and flow changes associated with the procedure have been few.

**FIGURE 6.** Pressure measurements in the left atrium. For details, see legend to figure 2.

**FIGURE 7.** Pressure measurements in the right atrium. For details, see legend to figure 2.
Lucas et al. found a statistically significant intraoperative reduction in pulmonary blood flow after open closure. No significant intraoperative changes in the pressures in the pulmonary artery or pulmonary veins or in heart rate were found. Cassels and Sodt, using a venous occlusion plethysmograph, demonstrated an increase in postoperative peripheral blood flow to the arms after closure of secundum type ASDs.

Several authors have compared ASD patients with normal control subjects. Levin et al. found statistically significantly lower left ventricular stroke work and stroke volumes in patients with ASDs. and in those

**FIGURE 8.** An example of flow measurements from the ascending aorta. Both pulsatile flow (top) and mean flow (bottom) are seen. At the ordinate is flow (liters/min) and at the abscissa, time (sec).

**FIGURE 9.** An example of the flow measurements from the right pulmonary artery. See legend to figure 8 for details.
with high-shunt ASDs, they found lower cardiac indexes and peak aortic systolic pressures. They were unable to demonstrate differences in the left ventricular end-diastolic, right atrial, right ventricular end-diastolic, or pulmonary arterial pressures. Popio et al. confirmed the lower left ventricular volumes in patients with ASDs and demonstrated abnormal contraction of the septum and apparently decreased distensibility of the myocardium. Wanderman et al. confirmed the diminished volume of the left ventricle but found no impairment of contractility. Liberthson et al. demonstrated a consistently dilated right ventricle before surgery. The dilatation diminished after surgery. Flamm et al. noted diminished cardiac output and left ventricular end-diastolic pressures in patients with ASDs compared with those in an age-related group. It is thus generally accepted that patients with ASDs of the secundum type have right-sided dilatation and hypertrophy and assumed that stroke volume of the left ventricle and peripheral cardiac output are diminished. The function of the left ventricle is generally considered to be normal, although some disagree. A smaller diameter of the aortic arch in patients with ASDs has been considered characteristic, but this could not be demonstrated by DeMaria et al.

In our investigation the circumclusion method was found to be an excellent experimental model for the purpose described. It was unambiguously confirmed that significant increases in the pressures in the left atrium, ascending aorta, and right pulmonary artery and in flow in the ascending aorta immediately follow closure of an ASD of the secundum type. Corresponding significant decreases in pressure in the right atrium and in flow in the right pulmonary artery were also confirmed. No changes in heart rate or in pressure in the right ventricle could be demonstrated. The immediate increases in pressures on the left side of the heart and in cardiac output when the shunt was closed are

![Graph showing flow measurements from the ascending aorta (left) and right pulmonary artery (right). Each column illustrates results when the ASD is open and closed. At the ordinate is the flow (ml/min/kg) and on each of the four ordinates the mean flow is labeled. At the bottom of each column the p value is listed (see legend to figure 2).](http://circ.ahajournals.org/)

**FIGURE 10.** Flow measurements from the ascending aorta (left) and right pulmonary artery (right). Each column illustrates results when the ASD is open and closed. At the ordinate is the flow (ml/min/kg) and on each of the four ordinates the mean flow is labeled. At the bottom of each column the p value is listed (see legend to figure 2).

![Graph showing intraoperative pressure measurements from the left atrium when the ASD was closed and postoperative pressure measurements obtained at catheterization (pulmonary artery wedge pressure). The systolic (left), diastolic (middle), and mean pressures (right), are illustrated. For details see legend to figure 3.](http://circ.ahajournals.org/)

**FIGURE 11.** Comparison of intraoperative pressure measurements from the left atrium when the ASD was closed and postoperative pressure measurements obtained at catheterization (pulmonary artery wedge pressure). The systolic (left), diastolic (middle), and mean pressures (right), are illustrated. For details see legend to figure 3.
easily understandable and in good accordance with the findings of others.\cite{6-8,10} Both a mean increase from 74 to 84 mm Hg in mean aortic pressure and from 84 to 111 ml/min/kg in flow in the ascending aorta will immediately increase the work of the left ventricle. This might explain the acute left heart failure after surgical closure of ASDs that has been reported.\cite{12} In connection with a mean increase in the mean pressure in the left atrium from 10 to 18 mm Hg, the risk of postoperative overloading must increase. After closing the shunt, one might expect a decrease in the pressure in the pulmonary artery but, on the contrary, both diastolic and mean pressures increased in this vessel. This could be explained by the simultaneous increase in the pressure in the left atrium since a positive correlation was found between the pressure increases. This relationship seems probable because the increased pressures in both the left atrium and in the pulmonary artery were normalized 3 to 12 months after surgery. A positive correlation between shunt size determined before and during surgery should be expected. Although this was not a finding of our study, several factors might contribute to erroneous results. The intraoperative determination was made in anesthetized patients placed on their left sides and the preoperative determination in patients who were awake and supine. To perform the dissection necessary for positioning of the encircling suture it was also necessary to partially compress the right lung. Thus, flow in the right pulmonary artery might not have been the same as in the left pulmonary artery. Furthermore, it was often technically difficult to determine the zero point on the flow curve from the right pulmonary artery. It would have been better to measure the flow in the main pulmonary artery, but it was almost always impossible to place the probe there. The flow decreased from 78 to 46 ml/min/kg, which is a small decrease in relation to the intraoperative mean shunt of 159% of peripheral cardiac output. However, a decrease of this order should not be expected since the peripheral cardiac output simultaneously increased when the shunt was closed. It should also be mentioned that flow in the ascending aorta equaled the peripheral cardiac output and that no measures were taken to determine influence of the flow in the coronary arteries. In spite of these possible sources

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{figure12}
\caption{Comparison of intraoperative pressure measurements from the right pulmonary artery when the ASD was closed and those obtained at the postoperative catheterization. See legends to figures 3 and 11 for details.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{figure13}
\caption{Comparison of intraoperative pressure measurements from the right ventricle when the ASD was closed and those obtained at the postoperative catheterization. For details see legends to figures 3 and 11. (Mean pressures are not shown.)}
\end{figure}
of error, the lack of correlation between the shunt values is surprising. Findings from the oldest patients, who were receiving medical treatment for congestive heart failure, were evaluated separately but no differences were found between them and the rest of the patients. This is also unambiguously illustrated in the results presented in figures 3 to 7 and 10. Finally, the fact that the period during which the intraoperative measurements were made was so brief should be emphasized, the interval of occlusion being a maximum of 1 to 2 min. When we compared intraoperative results with the ASD open and those with it closed, the patients always served as their own controls. When we compared intraoperative with postoperative results, however, this is not the case, and errors caused by different pressure transducer levels might have contributed to erroneous results. The intraoperative pressure transducer level when the patient was lying on the left side was the mid-sternal niveau and that at the postoperative catheterization, when the patient was in supine position, was the midaxillary niveau. This may have caused a systematic error that resulted in measured intraoperative right atrial pressures that were too high. However, this alone could not explain the marked decreases found after surgery; these decreases were not only found in the right atrium but also in the left atrial/pulmonary capillary wedge, pulmonary arterial, and right ventricular pressures. Our results thus confirm that the above-mentioned increases in intraoperative pressures after closure of ASDs will be normalized 3 to 12 months after surgery.

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