Quantitative aspects of right-to-left shunting in uncomplicated atrial septal defects

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The net right-to-left shunt in patients with atrial septal defects was quantified by means of polarographic determination of arterial P_{O_2} during pure oxygen breathing. Fifty-five per cent of the patients had an abnormally low P_{O_2} when compared with a normal control group. Pulmonary venous oxygen tensions were normal, confirming that most of the shunting actually takes place in the atrium. The haemodynamic measurement which correlated best with the magnitude of the right-to-left shunt was the height of the a-wave in the right atrium. This is consistent with the concept that the right-to-left shunting mainly occurs during the small interval in which right atrial systole precedes left atrial systole. No difference in shunting was found between atrial septal defects of the primum and secundum types.

It is commonly accepted that right-to-left shunting occurs in patients with atrial septal defects complicated by advanced right ventricular hypertension. It is also known (Marshall, Helmholtz, and Wood, 1962; Dexter, 1956) that a large proportion of patients with uncomplicated atrial septal defects may have a small right-to-left shunt at the atrial level. We found, however, that both the incidence of such a shunt and the possible influence of other haemodynamic variables upon shunt size had been insufficiently documented with a sensitive technique. This report represents an effort to do so, using arterial oxygen tension measurements for the determination of shunt volume.

Subjects and methods

In our department arterial oxygen tensions have been routinely determined during air and pure oxygen breathing in patients with atrial septal defects. In this study 73 consecutive patients with atrial septal defects and without other cardiac lesions were selected. All had a dominant left-to-right shunt and none had an Eisenmenger syndrome (Wood, 1958). Two had defects of the primum type, the others had secundum defects. The group was compared with a control group consisting of 52 subjects without known heart or lung disease, most of whom had been referred to the department because of an innocent heart murmur. All subjects in both groups were above 15 years of age.

A subsample of 28 patients with atrial septal defects and sinus rhythm, 2 of the primum and 26 of the secundum

type, was selected for the correlation of right-to-left shunt volume with other haemodynamic variables. In this group right heart catheterization had been performed within a few days of the oxygen tension measurement.

In order to compare oxygen tensions in the systemic arteries and the pulmonary veins, blood samples were drawn simultaneously from these two sites during right heart catheterization in 6 patients.

Blood oxygen tension was measured by means of the polarographic technique using a coated platinum electrode (Eschweiler, Kiel) (Polgar and Forster, 1960; Severinghaus, 1965). The electrode was calibrated immediately before each measurement by means of four gases with exactly known oxygen contents of about 2, 12, 50, and 95 per cent. Only electrodes giving stable calibration measurements were used. The samples were analysed immediately after blood withdrawal. The tension was first measured during air breathing and then after 10 minutes of 100 per cent oxygen breathing, with the patient in the supine position. Arterial PCO_2 was measured with the Astrup technique.

The net right-to-left shunt was calculated from the measurements made during pure oxygen breathing, thus excluding hypoventilation and perfusion-ventilation disturbances as sources of 'shunting' (Mellemegaard, 1966). Arteriovenous oxygen difference and cardiac output measured during right heart catheterization was used. The shunt was calculated from the commonly applied formula (McIlroy, 1965; Holmgren and Svanborg, 1965):

$$\frac{Q_s}{Q} = \frac{C_{aO_2} - C_{vO_2}}{C_{vO_2} - C_{vO_2}}$$

where Q_s and Q are the shunt and systemic blood flow

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respectively, C_{cO_2} is the pulmonary end-capillary oxygen content, C_{aO_2} the arterial oxygen content, and C_{vO_2} the mixed venous oxygen content. Complete nitrogen wash-out was assumed to occur during the 10 minutes of oxygen breathing.

Results

Incidence of abnormal right-to-left shunts

Arterial oxygen tensions during oxygen breathing in patients with atrial septal defects and control patients are shown in Fig. 1. Since the mixed venous oxygen content was unknown in some cases the tensions were compared directly, but almost identical distributions resulted from the comparison of the computed right-to-left shunts. It is seen that 38 per cent of the subjects with atrial septal defects had oxygen tensions below 560 mmHg, which was the lowest value in the control group. Fifty-five per cent of the patients had values below the normal 4th percentile. The difference between the two groups is highly significant ($P < 0.001$). The upper normal right-to-left shunt in this material was thus about 5 per cent, in good agreement with previously reported values (Mellemaard, 1966).

Origin of shunt

In atrial septal defects the pulmonary blood flow may be up to five times the systemic. A possible, though improbable, source of arterial hypoxaemia in this state might be the opening of pulmonary

TABLE Oxygen tensions in simultaneously drawn blood samples from femoral artery and pulmonary vein in 6 subjects with atrial septal defects

Case No.	Defect type	P_{O_2} Femoral artery	Pulmonary vein
1	Secundum	526	627
2	Primum	560	635
3	Secundum	540	605
4	"	590	620
5	"	500	595
6	"	400	590
Mean		519	612

arteriovenous shunts or the high flow impairing the complete oxygenation of blood during capillary passage. The oxygen tensions from the pulmonary veins (Table) were, however, essentially normal.

Haemodynamic determinants of right-to-left shunt size

The shunt size was correlated with pressure and flow measurements obtained during right heart catheterization and with the radiologically determined heart volume. Various combinations of these data, which were thought to have possible physiological significance, were also tested. The best con-

FIG. 1 Distribution of arterial oxygen tensions in normals and patients with uncomplicated atrial septal defects ($P < 0.001$).

FIG. 2 Relation between right-to-left shunt size and the height of the right atrial a-wave in subjects with uncomplicated atrial septal defects.

FIG. 3 Relation between right-to-left shunt size and pulmonary arteriolar resistance in subjects with uncomplicated atrial septal defects.

relation was that between shunt size and the height of the a-wave in the right atrium (Fig. 2), this correlation being better than with any estimate of differential interatrial pressure. In most cases the interatrial pressure difference had to be calculated from the pulmonary wedge pressure, which is a too indirect measure of instantaneous left atrial pressure. Even the height of the right atrial a-wave only accounted for about 28 per cent of the total variation in the shunt. Pulmonary arteriolar resistance also correlated significantly with shunt size, even at this low resistance level (Fig. 3). The other relations were not significant statistically.

Six primum defects, 4 of which had significant mitral regurgitation, were compared with 26 secundum defects with comparable left-to-right shunts and pulmonary artery pressures. No difference in the size of the right-to-left shunt was found.

Discussion

Right-to-left shunting in atrial septal defects is commonly evaluated by measuring arterial oxygen content, which may be done with an accuracy of about ± 1.5 ml/l. (McIlroy, 1965). Using this method, Dexter (1956) made an analysis of right-to-left shunting in a large number of patients with atrial septal defects. He found that about one-third had oxygen saturations below the normal limit of 95 per cent. However, when the pulmonary arteriolar resistance was in the range considered here, the number of

patients with an abnormally low saturation was much lower, about 15 per cent. The oxygen tension may be estimated with an accuracy up to 10 times that of O_2 content (McIlroy, 1965), and may thus give a much better separation between normal and abnormal. In addition, the method applied serves to exclude alveolar hypoventilation and ventilation perfusion disturbances as causes of hypoxaemia. The present study is probably the first in which a large number of patients have been investigated with a sensitive technique. This is reflected in the finding of a higher percentage of patients with abnormal right-to-left shunts than in previous reports (Dexter, 1956).

Indicator dilution technique (Swan, Burchell, and Wood, 1954), angiography (Levin *et al.*, 1968), and direct measurement of flow by Doppler ultrasound (Kalmanson *et al.*, 1972) have also been used for the estimation of the right-to-left shunt in a few patients with atrial septal defects. The angiographic and Doppler methods estimate total right-to-left shunt which passes the defect, much of which is washed back to the right atrium shortly afterwards. In contrast, both the indicator method and the oxygen tension method determine net right-to-left shunting.

The direct effect of pure oxygen on the vascular bed may represent one possible source of error in the present work. This factor could give an underestimation of the right-to-left shunt (Douglas *et al.*, 1969). Strained respiration during oxygen breathing might, on the other hand, increase the shunting (Landrigan and Cudkowicz, 1962). However, we consider it improbable that these factors were significant.

The exclusive localization of the pathological shunt to the atrial level was not unexpected from general knowledge (Comroe *et al.*, 1962) and from previously reported oxygen saturation data (Hickham, 1949).

Interatrial shunts are essentially dynamic in nature and are primarily influenced by very small changes in differential interatrial pressure (Levin *et al.*, 1968). This may be influenced by several factors, including heart rate (Levin *et al.*, 1968) and respiration (Gamble *et al.*, 1965). The present pressure measurements were made with conventional arterial transducers and heart catheters and the instantaneous differential interatrial pressure was not measured exactly. Right-to-left shunt and pressures were not measured simultaneously. It is therefore not surprising that none of the correlations between pressures and right-to-left shunt size was high. The finding that pulmonary arteriolar resistance was a determining factor of shunt size is in accordance with previous reports (Dexter, 1956) and in agree-

ment with the concept that shunt dynamics in atrial septal defects are determined by the compliance of the two ventricles. Right ventricular compliance is even at this low pressure level primarily determined by the pulmonary vascular resistance.

The observation that the height of the a-wave in the right atrium was the best determinant of shunt size, was, however, somewhat more surprising. Levin *et al.* (1968) have reported that the right-to-left shunt occurs during the isometric phase of ventricular contraction and during early ventricular diastole. Using Doppler ultrasound flow measurement, Kalmanson *et al.* (1972) found an early systolic right-to-left shunt only. Others have maintained that reversal of the interatrial pressure gradient only occurs during atrial systole (Shaffer, Silber, and Katz, 1954). The latter is supported by the present observation that the right atrial a-wave alone was the best predictor of shunt size. It is established that right atrial systole starts on average 20 milliseconds before that of the left (Braunwald, Fishman, and Cournand, 1956; Little, Opdyke, and Hawley, 1949; Shaffer *et al.*, 1954). During this short interval right atrial systolic force may act more or less unopposed and may thus produce most of the right-to-left shunt. The different methods used for measuring the shunt, some determining total and others net right-to-left shunt may explain some of the difference in opinion regarding the timing of the shunting.

In the present study no difference in right-to-left shunting was found in primum and secundum defects. This is contrary to the common belief (Swan *et al.*, 1954; Winters *et al.*, 1967; Silver, Kirklin, and Wood, 1956) that there is a preferential blood flow from the inferior vena cava through an atrial septal defect and that there is a relation between right-to-left shunt size and localization of defect. A possible factor in this comparison may be that the mitral regurgitation commonly found in AV septal defects may counteract net right-to-left shunting through the washing back of blood through the defect in ventricular systole.

Although the practical importance of the present observations is limited, they may serve to elucidate shunt mechanics in atrial septal defects and to emphasize that comparatively large right-to-left shunts may be found in uncomplicated atrial septal defects.

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