A Study of Hydraulics in Simulated Patent Ductus Arteriosus

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A hydraulic model was designed to study the effects of converging streams such as occur in patent ductus arteriosus. The results showed that flow across the fistula was dependent primarily on the resistance at the outlets of the "systemic" as against the "pulmonic" circulation. Even very slight differences in resistance could effect very large shunts. When the left ventricular output was great, the loss across the shunt was relatively unimportant. However, when the left ventricular output was low, most of its flow passed across the shunt and the systemic delivery virtually ceased. This situation became much more severe if the systemic resistance was raised even slightly above that of the pulmonic outflow path.

In patent ductus arteriosus, the complexity of the patterns of impingement of the two streams has prevented an adequate analysis of the interrelations between them. For example, certain apparently anomalous situations may occur in which there may be a great increase in flow across the shunt without producing an appreciable rise in pulmonary arterial pressure. Experimental studies on animals have certain limitations because of the secondary adjustments which are brought about by changes in the function of the heart and of the vasomotor apparatus.

To provide a base line for studies on the dynamics of such communications, the hydraulics of a connection between two streams was studied in glass models. For convenience the sources in the model, are labelled right or left ventricle, respectively, the conveying tubes are called pulmonary artery and aorta and the outlets are named systemic and pulmonary resistances.

General Methods

A reservoir hanging at a fixed height, provided a "left ventricular" pressure head which produced flow through an aorta to an outlet placed at its end. The reservoir height as well as the outlet level (systemic resistance) could be adjusted as desired. A similar arrangement at a lower level provided a "right ventricular" pressure which produced flow against a predetermined outlet pressure head (pulmonary resistance) (fig. 1). The communication (F), hereafter called "fistula," could be open or closed. Flowmeters established the separate rates of flow from each reservoir. The delivery from each of the two outlets (systemic and pulmonary) was collected in graduated cylinders and the deliveries were determined per unit time. Tap water (15 C.) was used throughout.

Results

Flow through Isolated Channels

With the fistula closed, delivery from the isolated right or left ventricles was determined for several pressure heads. Data are given in figure 2 as the two lines labeled LV (no fistula) and RV (no fistula).

Left Ventricle: The left ventricular pressure head was set at each of 10 or more levels in order to establish rates of flow through the system (LV in fig. 1). At a pressure head of 20 cm. the flow was 430 ml./min.; at 40 cm. it was 1435 ml./min.; at 80 cm. it was 2470 ml./min. and at 100 cm. it was 2840 ml./min.

Right Ventricle: This reservoir was set at three pressure levels, 18, 20 and 30 cm. water. Flow through this isolated pulmonary system for the 18 cm. pressure head was 500 ml./min.; at 20 cm. it was 660 ml./min. (RV in fig. 1); and at 30 cm. it was 1405 ml./min. Data for
20 cm. water pressure head are given in figures 2 to 6 as dotted lines labelled RV (no fistula).

These data, showing a relatively linear relationship between pressure and flow, serve as a base line for the fistula experiments.

Establishment of the Fistula

When the glass tube (F), 0.8 cm. in diameter and 10 cm. in length was open, the total flow out of the entire system was unchanged. However, as shown in figure 2, flow from the left ventricle was slightly facilitated (LV [fistula]), while that from the right ventricle (RV [fistula]) was reduced by an equal amount. For example, isolated flow was 2840 ml./min. from the left ventricle with a pressure head of 100 cm. water; it increased to 2950 ml./min. when a fistula connected the aorta to the pulmonary artery (right ventricle head, 20 cm.). The right ventricular delivery fell at this time from 660 to 550 ml./min., indicating the increased resistance acting on its outflow channel. It is evident that the presence of the fistula, by permitting cross-over flow from the site of higher pressure and thereby increasing the resistance to delivery from the right ventricle, reduces the output of the latter.

Because of the crossing of flow at the level of the fistula, the volume of delivery at each of the systemic and pulmonary outfalls approached a common value (fig. 2). Thus, approximately 53 per cent of the flow fell from the systemic outlet and the remainder (47 per cent) fell from the pulmonary outflow outlet for almost the entire range of aortic pressures used.

These data demonstrate that the opening of a fistula facilitates flow from a higher pressure left ventricular reservoir, probably because of the added availability to it of a low resistance outfall in parallel with its normal outfall channel. Conversely, the flow across the fistula reduced the delivery from the right ventricular reservoir. If the right ventricle were then to deliver its original volume, a somewhat higher right ventricular pressure head would be required. A very slight increase in right ventricular pressure head (2 to 5 cm. H2O) was sufficient to do this.

The volume crossing the fistula appeared to be determined primarily by the resistances at each outlet.

The Effect of Outlet Resistance

As a matter of convenience, pulmonary outflow resistance was kept constant and systemic resistance was varied.
When the left ventricular reservoir pressure was set at 40 cm. H$_2$O and right ventricular pressure at 20 cm. water, the presence of a systemic outlet resistance of 1 cm. H$_2$O reduced systemic flow from 1140 ml./min. (fig. 2) to 890 ml./min. (fig. 3), a reduction of 23 per cent from the values obtained when the outfall resistances were equal. This 240 ml. difference was deviated to the pulmonary outlet. A very slight dysbalance in outlet resistances thus produced profound effects on flow at these low driving heads.

At higher left ventricular pressure heads (100 cm.) the effects of difference in outlet resistance of 1 cm. were relatively slight. Delivery from the right ventricle was slightly reduced, and that from the left ventricle was increased. The deviation from the systemic circuit across the shunt amounted to only 100 ml. or 5 per cent of flow from the left ventricle.

These effects become more striking as the systemic outlet resistance was raised to 3 cm. water (fig. 4). Now a left ventricular pressure head of 40 cm. delivered only 550 ml./min. to the systemic periphery, i.e. only about one-third of the left ventricular output. The deviated flow passed through the pulmonary outlet. At a left ventricular head of 100 cm., the effect of the 3 cm. resistance was insignificant (compare systemic flows in figs. 2 and 4). The supplementary deviation from left ventricle to pulmonary outlet due to the added systemic outlet resistance amounted to only 6 per cent.

At the 40 cm. left ventricular pressure level, a systemic vascular resistance of 7 cm. water brought the delivery from this outlet to a complete halt (fig. 5). All the flow from both reservoirs now was presented to the pulmonary outlet, almost doubling its delivery, compared with the situation when the resistances were equal.

At a left ventricular pressure head of 100 cm., the 7 cm. aortic resistance caused a deviation of 31 per cent of the systemic flow to the
pulmonary vessels (1895 ml./min. reduced to 1310 ml./min.).

For left ventricular pressures less than 60 cm. water, a systemic outlet resistance of 12 cm. caused all the fluid from both reservoirs to leave the system via the pulmonary outlet tube (fig. 6). At 100 cm. left ventricular driving pressure, the systemic outlet received only about 30 per cent of the flow it had obtained with a balanced resistance.

The total flow from the two reservoirs was reduced by 17 per cent as a result of this single outlet resistance of 12 cm. Delivery from the pulmonary reservoir ceased completely. Nevertheless, flow through the pulmonary outlet, as a result of the deviation of aortic flow, was three times that taking place when there was no fistula.

The results illustrate the tremendous effect of even small dysbalances in the outlet resistances on the ultimate distribution of the ventricular outputs. These effects were most striking when the left ventricular pressure and output were low. At higher left ventricular outputs and pressures the effects of a dysbalance of small magnitude were still present but of much less importance, at least in terms of the systemic delivery.

The outlet resistance reduces flow through the entire system as a result of two related effects: (1) the obstacle at one of the outlets deviates much of the flow through the opposite tube and thereby reduces the effective cross-section area through which the total outflow must pass, and (2) flow from the right ventricle and pressures the effects of a dysbalance of small magnitude were still present but of much less importance, at least in terms of the systemic delivery.

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The volume passing through a shunt will depend on the pressure gradient across it and on its cross section area. In the present study we used a fistula of constant cross section area sufficiently great to accommodate a large shunt. Under these conditions, the deliveries through the systemic and pulmonary vascular systems tended to equalize when both resistances to outfall were equal or "balanced." The fistula provided a second outlet for the left ventricular high pressure source, reducing its total resistance and enhancing delivery from it. This reduced total peripheral resistance would normally tend to bring about a fall in the aortic pressure. In the present study, this complication was prevented by using reservoirs at fixed pressure heads.

The shunted flow from the high pressure left ventricular system into the pulmonary outlet acts as a hindrance to delivery from the low pressure of the right ventricle. Under normal circumstances in the body, the right ventricle would be called upon to increase its work and raise its pressure sufficiently to deliver the blood returning to it. A modest rise in pressure in the right ventricle appears to be sufficient to accomplish this. The shunted blood flows rapidly through the lung, arrives at the left heart and increases the minute output of the left ventricle. The results of this new equilibrium produced by the fistula is a heightened pressure load on the right ventricle and an increased volume load on the left ventricle. The effect on the lung is to produce congestion of the pulmonary vessels because of the enhanced blood flow through them and a slight increase in pulmonary arterial pressure may ensue.

In the fetus, the high resistance to flow into the pulmonary parenchyma diverts the right ventricular output into the descending streamlines of the aorta and thence to the placenta. With the onset of ventilation the pulmonary resistance is lowered and the flow is shunted preferentially to the lungs. If the pulmonary vascular resistance remains high however, flow through the ductus may continue and perhaps may lead to its persistence. In the adult with a patent ductus arteriosus, our data may be considered as showing that as long as the left ventricular output is ample and the aortic pressure remains high, some delivery from the left ventricle to systemic vessels will take place, even against the higher resistance of the systemic circuit. The extraordinarily low resistance to flow through the normal lung permits a sufficient pulmonary perfusion even were the systemic resistance to fall. A high pulmonary vascular resistance, such
as occurs in some congenital anomalies, might tip the balance in the opposite direction and cause the shunt to pass from right to left with the production of cyanosis.

The data have particular interest in the analysis of the situation in which the systemic pressure is low, as in the infant with a large ductus. When the pressures of the two circuits are nearly equal, a very slight increase in the vascular resistance of one of the outlets can virtually stop flow through that outlet. Thus, the naturally increasing systemic peripheral resistance which comes with growth may shunt so much of the left ventricular output through the lungs that the ductus may take on a malignant aspect, despite the fact that no significant pulmonary hypertension may be present.

The present in vitro experiments may thus provide a degree of insight into some of the hydraulic characteristics of patent ductus arteriosus.

**SUMMARY**

To analyze the hydrodynamics of patent ductus arteriosus, flow in two streams joined by a fistula was studied in a specially designed model.

Flow across a short wide fistula is dependent primarily on the pressure gradient across it. A large shunt flow acts to increase the resistance offered to delivery from the lower pressure side of the system (right ventricle), thus requiring the development of a higher pressure in this chamber, if its original volume output is to be maintained.

A second factor determining distribution of flow is the differences in the resistances supplied at the two outlets (peripheral vessels). When both pressure heads are low or equal, a very slight unilateral increase in vascular resistance can seriously reduce the delivery to that side. At high pressure heads and flow rates this effect is relatively much less important.

A persistent ductus of the type described produces a hydraulic volume load on the left ventricle and a pressure load on the right ventricle.

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