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. H$_2$O) 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 dyshalance 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 a left ventricular pressure head of 100 cm., 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. Never-
theless, 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 re-
sistances 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 out-
puts 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
is brought to a halt by the combination of the
outlet resistance and the high left ventricular
pressure and flow which transmit a "back
pressure" to this reservoir.

**DISCUSSION**

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 resis-
tance and enhancing delivery from it. This
reduced total peripheral resistance would nor-
mally tend to bring about a fall in the aortic
pressure. In the present study, this complica-
tion 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 height-
ened 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 en-
hanced 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 stream-
lines 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 per-
haps may lead to its persistence.6 7

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 extra-
ordinarily 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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