A Study of Hydraulics in Simulated Patent Ductus Arteriosus

By Simon Rodbard, M.D., Ph.D., Robert Zaas, B.S. and William Cook, B.S.

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.
Figs. 3 to 6. Effects of added systemic vascular resistance equivalent to 1, 3, 7 and 12 cm. H$_2$O respectively. Conventions as in figure 2. Discussed in text.

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 dysharmony 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.

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.

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.

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.

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.
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.

ACKNOWLEDGMENT

We are grateful to Dr. G. V. LeRoy of the Department of Medicine of the University of Chicago for aid in facilitating this study.

REFERENCES

A Study of Hydraulics in Simulated Patent Ductus Arteriosus
SIMON RODBARD, ROBERT ZAAS and WILLIAM COOK

Circ Res. 1955;3:613-617
doi: 10.1161/01.RES.3.6.613

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1955 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/3/6/613

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation Research can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation Research is online at:
http://circres.ahajournals.org/subscriptions/