Demonstration of Preferential Flow of Blood From Inferior Vena Cava and From Right Pulmonary Veins Through Experimental Atrial Septal Defects in Dogs

By ARTHUR W. SILVER, M.D., JOHN W. KIRKLIN, M.D., AND EARL H. WOOD, M.D., PH.D.

Preferential right-to-left shunting of inferior vena caval blood and left-to-right shunting of right-lung blood has been demonstrated to occur in experimental atrial septal defects in dogs as in the congenital defects in human beings. Existence of these preferential shunts proves that uniform mixing of blood does not occur in either atrium.

Utilizing a technic of continuously recording the dilution pattern of an indicator substance, Swan, Burchell and Wood have demonstrated some interesting patterns of flow of blood in patients with atrial septal defects. By injecting Evans blue dye (T-1824) into the venae cavae they obtained dilution patterns indicating that some of the caval blood crossed the atrial septal defect from the right atrium to the left atrium. The greater portion of this right-to-left shunted blood came from the inferior vena cava. By this same technic they also showed that the right lung contributes most of the blood shunting in the usual left-to-right direction through atrial septal defects.

These authors attributed this phenomenon of preferential flow to the proximity of the vessels involved (that is, right pulmonary veins and inferior vena cava) to the defect in the atrial septum. Some confirmation of this explanation has come from postmortem study of hearts with congenital atrial septal defects. Further confirmation was obtained by exploration of the heart during surgical repair of the defects.

The study herein presented was undertaken to provide information concerning preferential flow across experimental atrial septal defects in dogs.

Methods

The atrial well technic of Gross and associates was employed to gain access to the atrial septum. This method has the advantage of permitting access to all parts of the septum. The heart was entered via the right atrium in nine dogs weighing from 14 to 25 Kg. An attempt was made to excise as much septal tissue as possible. This was done by employing the instrument devised by Griffin and Essex for the creation of interventricular septal defects to excise and retain the tissue removed from the septum.

Approximately 3 months after operation the dogs were studied by cardiac catheterization. During the study the animals were anesthetized with sodium pentobarbital (25 mg./Kg. of body weight given intravenously) and were breathing 100 per cent oxygen through an endotracheal tube. Dye-dilution curves were recorded in blood flowing from the dog's femoral artery through a cuvette oximeter after injections of 20 mg. doses of T-1824 into various sites. These sites included both venae cavae, the left pulmonary artery and as many lobar branches of the right pulmonary artery as could be entered by manipulation of the catheter under fluoroscopic guidance.

Pressures transmitted through the cardiac catheter, pressures in the femoral artery, respirations, an electrocardiogram and the dye-dilution curves were recorded by means of a photokymographic assembly previously described. The type of recording obtained is illustrated in figure 1 showing the dye-dilution pattern in a normal dog.

Seven of the 9 dogs were killed with overdoses of sodium pentobarbital shortly after cardiac catheterization study. The hearts and lungs were carefully examined, particular attention being paid to the size of the atrial septal defects, location of the defects.
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FIO. 1. Portion of arterial dilution curve recorded at femoral artery after injection of T-1824 into right pulmonary artery of a normal dog. S.S., IR and R indicate the traces of the single-scale and double-scale infrared and red galvanometers of cuvette oximeter respectively. Scale: 10 seconds = 5.0 cm.

RESULTS

Vena Caval Injections. After injection of dye into the inferior vena cava (at or just below the diaphragm) the contours of the dye curves of 7 of the 9 dogs were found to be similar to those described by Swan, Burchell and Wood1 in which some right-to-left shunt of blood was indicated from this vessel. Such a contour (fig. 2) consists of a relatively short appearance time of the dye (as compared, for example, with the appearance time after injection into a left pulmonary artery) and a break or initial hump on the build-up slope of dye concentration. This may be interpreted in the following manner: after injection into the inferior vena cava, a portion of the dye passed across the atrial septal defect into the left atrium. This portion of dye then passed through the left ventricle into the systemic arterial circulation where the first concentration peak was recorded. The remainder of the dye passed through the right atrium, right ventricle and the pulmonary vascular bed before reaching the left atrium, the left ventricle and, eventually, the systemic arterial recording site and caused a second concentration peak somewhat later than the initial concentration peak caused by that part of the dye that traversed the shorter pathway through the defect.

Only 4 of the dogs showed this contour after injections of dye into the superior vena cava. Except for 1 dog, B-459, the magnitude of this superior caval shunt was less than that from the inferior cava. In 5 dogs no initial break on the build-up slope of the superior caval curves was seen, indicating that in these animals superior vena caval blood did not participate in the right-to-left shunt. In 1 dog a right-to-left shunt could not be demonstrated from either vena cava. Employing the method of Swan, Zapata-Diaz and Wood9 the magnitude of the shunt from the inferior cava was estimated to average 14 per cent (0 to 40 per cent) of the pulmonary flow, whereas the right-to-left shunt from the superior cava was much less, averaging 2 per cent (0 to 5 per cent) of the pulmonary flow.

As in human beings with congenital atrial septal defects, the disappearance time of the dye was prolonged in all dogs with surgically created defects.10 This result is caused by recirculation of part of the dye through the right atrium, right ventricle and pulmonary vessels after that dye has reached the left atrium and has been shunted left-to-right through the defect. Such a prolonged disappearance time is characteristic of dye curves in anomalies manifesting a left-to-right shunt.

Injections Into Pulmonary Artery. Injections into the left pulmonary artery were done in all 9 dogs. Except for some prolongation of the disappearance time of the dye, these curves
were not remarkable (fig. 3). In the animals in which injections were made into the right apical and cardiac lobe pulmonary arteries, an interesting "double-hump contour" was observed in the resulting dye curves (fig. 3).

This "double-hump" pattern may be explained as follows: The first peak in concentration (hump I in all curves, fig. 3) represents dye which, after passing through the respective lung or lobe, went through the left atrium and left ventricle into the systemic circuit and to the recording site. A relatively large portion of the dye injected into the apical and cardiac lobe branches of the right pulmonary artery was shunted across the atrial septal defect into the right atrium. This dye must recirculate through the lungs before traversing the left atrium and ventricle and only then enters the systemic circulation and the arterial recording site to produce the second peak in concentration. This second hump is, therefore, an accentuation of the prolongation of dye-disappearance time seen in lesions characterized by pulmonary recirculation. Dye curves for the left pulmonary artery in this group of dogs had a disappearance time approaching normal (fig. 3), an indication that much less of the left-to-right shunted blood came from the left lung.

The right apical lobe pulmonary artery could be entered by the catheter tip in only 3 dogs. All showed the contour described previously as indicating a preferential left-to-right shunt from this lobe. Injections into the right cardiac lobe were made in 6 dogs. All 6 animals likewise had preferential shunts from the right cardiac lobe. The right diaphragmatic lobe was the site of injection in 6 dogs, only 1 of which gave marked evidence of preferential left-to-right shunt from this lobe.

Anatomic Observations. The hearts and lungs of 7 of the experimental animals were studied at necropsy. The dog's atrial septum from the right atrial aspect presents two distinct parts. The portion occupying the caudal part of the septum and lying nearest the inferior vena caval orifice is composed of a thin sheet of muscle. This is the floor of the fossa ovalis. A semilunar ridge is formed just cephalad to this by a thick muscular column that comprises...
TABLE 1.—Size and Position of Surgically Produced Atrial Septal Defects and Relationships to Preferential Right-to-left Shunts

<table>
<thead>
<tr>
<th>Dog number</th>
<th>Diameter of defect (cm.)</th>
<th>Location</th>
<th>Limbus of fossa ovalis</th>
<th>Right-to-left shunt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ventrodorsal</td>
<td>Cephaloventral</td>
<td></td>
<td>From inferior vena cava</td>
</tr>
<tr>
<td>B-454</td>
<td>0.8</td>
<td>0.6</td>
<td>Floor of fossa ovalis</td>
<td>Intact</td>
</tr>
<tr>
<td>B-457</td>
<td>2.3</td>
<td>1.5</td>
<td>Floor of fossa ovalis</td>
<td>Absent</td>
</tr>
<tr>
<td>B-458</td>
<td>1.2</td>
<td>1.0</td>
<td>Floor of fossa ovalis</td>
<td>Small portion removed</td>
</tr>
<tr>
<td>B-459</td>
<td>0.5</td>
<td>0.5</td>
<td>Cephalad to limbus of fossa ovalis</td>
<td>Intact</td>
</tr>
<tr>
<td>B-494</td>
<td>—</td>
<td>—</td>
<td>Floor of fossa ovalis</td>
<td>Intact</td>
</tr>
<tr>
<td>B-566</td>
<td>1.3</td>
<td>1.4</td>
<td>Floor of fossa ovalis</td>
<td>Almost all removed</td>
</tr>
<tr>
<td>B-640</td>
<td>1.5</td>
<td>1.0</td>
<td>Floor of fossa ovalis</td>
<td>Small portion removed</td>
</tr>
</tbody>
</table>

Fig. 5. Right side of heart of one dog with a preferential right-to-left shunt detectable only from superior vena cava. Note small atrial septal defect, ASD, cephalad to limbus, L, of fossa ovalis and near the atrial orifice of superior vena cava, SVC. IVC, inferior vena cava.

In one dog, B-459, operated on early in this study, the defect was found to be quite small and lying cephalad to the limbus of the fossa ovalis (fig. 5). This, therefore, was quite close to the superior caval orifice and relatively far from the inferior vena cava. The limbus and floor of the fossa ovalis were intact. These necropsy findings were in perfect accord with the dye curves indicating that a small right-to-left shunt occurred from the superior vena cava although none could be demonstrated from the inferior cava.

An explanation on anatomic grounds also was found for the preferential left-to-right shunt from the right apical and cardiac lobes of the dog. The dog's right lung is composed of four lobes, namely the apical, cardiac, diaphragmatic and intermediate lobes. The latter two lobes, the diaphragmatic and intermediate, usually drain into the left atrium via a common channel. This venous channel enters the left atrium in its caudal and lateral aspect near the two orifices of the left pulmonary veins (fig. 6). These three pulmonary venous orifices lie relatively far from the atrial septum.

The right apical and cardiac lobe pulmonary veins, to the contrary, empty via two or three channels whose left atrial orifices are on the dorsal aspect of the left atrium very close to the atrial septum (figs. 6, 7). The left mainstem bronchus indents the wall of the left atrium just to the left of these pulmonary veins and produces a ridge in the atrium. When the atrial septum is defective, especially in its dorsal portion, the right apical and cardiac lobe pulmonary veins appear to drain chiefly into the right atrium. That they do drain in this manner functionally is borne out by the dye...
FIG. 6. Left atrium of heart of one dog used in this study. The two white pegs are in the right apical and cardiac lobe veins situated near the atrial septal defect, ASD. Note that orifices of two left pulmonary veins, LPV, and the right diaphragmatic lobe vein, RDPV, empty into left atrium at a greater distance from the atrial septal defect than orifices of right apical and cardiac lobes. SVC and IVC indicate superior and inferior vena cava respectively.

FIG. 7. Right atrium of heart illustrated in figure 6. Note juxtaposition of right apical and cardiac lobe pulmonary veins (two white pegs) to atrial septal defect, ASD. SVC and IVC, superior and inferior vena cava; L, limbus of fossa ovalis.

curves after injection into these lobes when contrasted with the curves obtained from the left lung and right diaphragmatic lobe whose pulmonary veins do not enter the left atrium in such close juxtaposition to the septal defect.

DISCUSSION

In human beings with congenital heart disease it is important, from the standpoint of surgical therapy, to differentiate functional anomalous pulmonary venous drainage from true anomalous connection of the pulmonary veins. Edwards applies the term “anomalous pulmonary venous connection” to the anatomic condition whereby one or more pulmonary veins fail to join the left atrium, but join the right atrium or a systemic vein. The term “anomalous pulmonary venous drainage” is reserved for the physiologic condition whereby pulmonary venous blood flows into the right atrium no matter by what route. One lesion which may entail anomalous pulmonary venous drainage without anomalous connection of the pulmonary veins is atrial septal defect. In the human being having a congenital atrial septal defect, as well as in the dog with an experimental lesion, dye-dilution technics have shown that the right pulmonary veins may drain functionally into the right atrium while anatomically terminating in the left atrium.

As indicated by the data presented herein, the cause of the preferential left-to-right shunt from the right lung is primarily anatomic. Although the shunt in patients with congenital atrial septal defects has not been localized as to which lobes of the right lung are primarily involved, this was possible in the dog. It is highly significant that the right apical and cardiac lobes were consistently involved in the preferential left-to-right shunt whereas the right diaphragmatic lobe was not. Since the two former lobes drain quite close to the septal defect while the diaphragmatic lobe vein lies some distance from it, the concept of the anatomic explanation of the preferential left-to-right shunt is borne out experimentally. In the human heart the right pulmonary veins lie much closer to the atrial septum than do those from the left lung. Thus the anatomic explanation of the preferential shunt from the right lung can also be applied in patients with atrial septal defects.

Likewise, an anatomic explanation has been shown experimentally to account for the small amount of right-to-left shunt from the inferior vena cava occurring across congenital atrial septal defects in human beings. These openings are often in juxtaposition to the inferior vena cava and relatively far from the superior cava. This anatomic arrangement was experimentally reproduced in the dog and a preferential right-to-left shunt from the inferior vena cava
similar to that seen in human beings was obtained. In 1 animal the appropriate anatomic relationships were established so that the defect lay near the superior vena cava. As might be expected, this animal had preferential right-to-left shunt from the superior cava.

The demonstration of preferential shunting of blood originating from the tributaries of the right and the left atrium proves that uniform mixing of blood does not occur before egress from either of these receiving chambers.

**SUMMARY**

It has been demonstrated by dye-dilution technics that in experimental atrial septal defects in dogs as in the congenital defects in human beings, preferential shunts frequently occur in both directions across the defect. A small portion of the blood entering the heart from the inferior vena cava is usually shunted preferentially in a right-to-left direction across the defect. A somewhat smaller shunt may come from the superior vena cava. Usually a greater portion of blood draining from the right lung is shunted in a left-to-right direction across the defect than from the left lung. In dogs this has been shown to occur especially from the apical and cardiac lobes of the right lung.

Data have been presented to confirm the concept that the cause of these preferential shunts is the proximity of the atrial septal defects to the inferior vena cava and the right pulmonary veins. Demonstration of these preferential shunts proves that uniform mixing of blood does not occur in either atrium.

**REFERENCES**


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