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ESTIMATION OF THE SIZE OF THE PATENT DUCTUS ARTERIOSUS FROM HEMODYNAMIC DATA

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The effects of patent ductus arteriosus upon the circulation were studied by Eppinger, Burwell, and Gross (1). Later, Dexter, Haynes, Burwell, Eppinger, Sosman, and Evans (2) described preoperative and postoperative hemodynamic studies obtained by cardiac catheterization in a patient with patent ductus arteriosus. Since the presence of a patent ductus arteriosus can be detected by physical examination in more than 95 per cent of the patients having this condition (3), cardiac catheterization studies are needed as an aid to diagnosis only where the murmur is atypical, or when there is a possibility of an additional abnormality. When the single lumen cardiac catheter is used, it may be very difficult to distinguish between shunts of oxygenated blood into the upper right ventricle and shunts into the pulmonary artery (4). At times, aortography may be needed to settle the diagnosis unless the cardiac catheter is passed through the ductus arteriosus.

Hemodynamic data may, however, be of assistance in estimating the size of the patent ductus arteriosus (5). This information may be of value in contemplating interruption of the ductus in very young children, or in adults over the age of forty. In addition, the suggestion of a very large channel may warn the surgeon of possible technical difficulties in its ligation or division.

This paper describes in twelve patients a comparison between the diameter of the ductus as measured at operation and certain hemodynamic observations obtained preoperatively. In the preoperative study, the following values were determined: increase in oxygenation of pulmonary arterial over mixed venous blood; volume of left to right shunt through the ductus; the internal diameter of the ductus arteriosus calculated from an orifice formula (5).

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MATERIAL

The subjects studied were twelve patients in whom the diagnosis of patent ductus arteriosus was made clinically. Their ages were from four to thirty-nine years (Tables I and II). The diagnosis of uncomplicated patent ductus arteriosus was made on the basis of a continuous or quasi-continuous murmur, maximal in the pulmonary valve area, the absence of cyanosis, the presence of a normal electrocardiogram, and chest x-rays showing normal or increased pulmonary vascular markings with slight or moderate enlargement of the left atrium and left ventricle.

METHODS

Cardiac catheterization of the right heart and pulmonary artery was done in the usual manner (6), using a single lumen catheter. Multiple blood samples were obtained from the pulmonary artery, right ventricle, right atrium, and one or both venae cavae, and analyzed in the Van Slyke apparatus. Pulmonary arterial samples for flow calculations were obtained from the distal right pulmonary artery. Following this, the catheter was quickly withdrawn, and samples were taken in rapid succession from the main pulmonary artery, right ventricle, right atrium, and venae cavae. Simultaneous pulmonary and systemic arterial pressures were obtained immediately after simultaneous pulmonary and brachial arterial blood samples. Pressures were measured by means of Hathaway strain gages and oscillograph or Sanborn transducers and Poly-Viso electrocardiograph. Systemic arterial pressure was measured through an indwelling needle in the brachial or femoral artery. In the adults, oxygen consumption was measured for flow calculations by collection of two-minute samples of expired air in Douglas bags, measurement in a Tissot spirometer, and analysis in the Haldane apparatus or in a Scholander micro gas analyzer. Simultaneous pulmonary and systemic arterial samples were taken over a one-minute period midway during the collection of expired air. In the children, oxygen consumption was calculated on the basis of surface area; these children were either sedated with one mg. of morphine per ten pounds body weight and three mg. of sodium phenobarbital per Kg. body weight, or were anesthetized with a combination of rectal and intravenous Sodium Pentothal®. Pulmonary flow, effective pulmonary flow, and left-to-right shunt were calculated from the formulae of Bing, Vandam, and Gray (7). Left-to-right shunt through the

ductus was calculated as the difference between total pulmonary flow and effective pulmonary flow. Pulmonary venous blood oxygen content was assumed to be 95 per cent of capacity unless the systemic arterial oxygen content exceeded this value; in those instances, pulmonary venous blood oxygen content was taken to be the same as that for systemic arterial blood. The theoretical internal diameter of the patent ductus arteriosus was calculated in accordance with the formula of Gorlin and Gorlin (5). The external diameter of the ductus was measured at operation with a caliper, either directly or with the aid of a piece of silk suture. Since the ductus was ligated rather than divided, its internal diameter was not measured. The length of the ductus arteriosus was also estimated at operation, and although this value must be considered an approximation, the theoretical internal diameter of the patent ductus arteriosus was then recalculated using a formula for the flow of a fluid through a pipe (8), based on Poiseuille's law.

RESULTS

The results are summarized in Tables I and II. All patients save one (M. C.) had normal saturation with oxygen of peripheral arterial blood. All patients had an increase in oxygen content of pulmonary arterial blood above that in the right ventricle or that in mixed venous samples from the right atrium. In two patients (A. F. and V. M.) the increase in arterial oxygen content of pulmonary arterial over right ventricular blood was of borderline significance. A significant increase in oxygenation of right ventricular blood over that in the right atrium was found in three patients (J. M., G. P., and V. M.). This was presumably due to insufficiency of the pulmonary valve (4). In the two latter patients, these samples were taken only two minutes apart. Location of the catheter tip was confirmed by pressure tracings in each instance. Disappearance of all murmur after ligation of the ductus is considered to have eliminated the possibility of ventricular septal defect as a cause of oxygenation of right ventricular blood. Patient G. P. was catheterized postoperatively and no evidence of increased oxygenation of right ventricular or pulmonary arterial blood was found. The calculated shunt through the ductus ranged from 0.8 to 17.1 liters per minute. Nine patients had mild or moderate pulmonary hypertension; three had normal pulmonary arterial pressures. Measurement of pulmonary wedge or "capillary" pressure was made in five patients. The only elevation (17 mm. mercury) was seen in a

TABLE I

Hemodynamic data in 12 patients with patent ductus arteriosus

Patient Age Sex	Systemic artery oxygen content cc./100 cc.	and % of cap.	Distal PA O₂ content cc./100 cc.	RV outflow O₂ content cc./100 cc.	Average rt. atrium O₂ content cc./100 cc. (Mixed venous)	Difference O₂ content cc./100 cc. and in % saturation*				Oxygen consumption cc./min.	Systemic flow L./min.	Effective pulm. flow L./min.	Pulm. flow L./min.	Shunt, left-right L./min.
						PA − MV %		PA − RV %						
1. A. L., 34, F.	16.8	94	14.7	9.6	9.7	5.0	29	5.1	30	209	2.9	2.9	10.0	7.1
2. C. W., 23, F.	15.0	96	13.0	10.1	10.1	2.9	19	2.9	19	205	4.2	4.2	10.3	6.1
3. I. M., 14, F.	17.0	97	14.6	13.1	12.0	2.6	15	1.5	9	206	4.1	4.1	8.6	4.5
4. W. T., 21, M.	19.4	100	17.4	15.7	15.2	2.1	12	1.7	9	231	5.5	5.5	11.6	6.1
5. F. T., 39, F.	12.1	98	10.5	7.3	7.0	3.5	28	3.2	26	186	3.6	3.6	11.6	8.0
6. G. P., 30, F.	17.9	96	16.8	14.6	12.8	4.0	20	2.2	10	240	4.7	4.7	21.8	17.1
7. A. F., 26, F.	16.3	95	12.9	12.1	11.8	1.1	7	0.8	5	213	4.7	4.7	6.3	1.6
8. C. D., 6, F.	13.7	97	11.9	8.9	9.2	2.7	19	3.0	21	119	2.6	2.6	6.6	4.0
9. M. C., 5, M.	14.3	90	12.3	11.4	11.5	0.8	6	0.9	6	123	4.4	3.2	4.0	0.8
10. P. S., 8, F.	13.9	93	11.7	9.5	9.5	2.2	15	2.2	15	126	2.9	2.6	4.8	2.2
11. V. M., 6, M.	17.3	93	14.0	13.2	12.0	2.0	11	0.8	4	118	2.2	2.0	3.0	1.0
12. L. L., 4, F.	15.6	99	12.9	10.4	9.8	3.1	20	2.5	14	72	1.2	1.2	2.7	1.5

* PA = Pulmonary Artery,
RV = Right Ventricle,
MV = Mixed Venous (average of right atrial samples).

TABLE II

Pulmonary vascular pressures; calculated and observed diameter of ductus in 12 patients with patent ductus arteriosus

Patient Age Sex	PA pressure* sys./dias. mean	Pulm. wedge pressure*	Systemic arterial pressure* sys./dias. mean	Shunt, left-right L./min.	Calculated internal diameter mm. (Orifice formula)	Measured external diameter mm.	Measured length mm.	Calculated internal diameter (Pipe formula)
A. L., 34, F.	— 44	—	— 150	7.1	5.8	18	—	—
C. W., 23, F.	— 29	—	— 112	5.7	5.6	9	2.5	3.1
J. M., 14, F.	— 23	11	— —	4.5	—	8	6.0	—
W. T., 21, M.	40/12 21	—	— —	5.0	—	10	3.5	—
F. T., 39, F.	26/16 20	17	149/62 93	8.0	6.8	10	10	4.9
G. P., 30, F.	24/14 18	—	111/56 77	17.1	10.2	14	10	6.2
A. F., 26, F.	19/11 15	10	113/65 86	1.6	3.0	5.4	6	2.9
C. D., 6, F.	38/26 33	—	120/69 88	3.1	5.0	10	6	3.9
M. C., 5, M.	27/8 18	—	100/57 64	0.8	2.4	5.5	7	2.8
P. S., 8, F.	— 16	8	140/81 110	2.2	3.2	5.5	7	3.0
V. M., 6, M.	32/19 25	—	95/42 66	1.0	2.8	8.5	8	3.2
L. L., 4, F.	18/15 16	8	88/45 64	1.5	3.2	7	7	3.2

* Pressures are expressed in mm. mercury.

woman of 39 (F. T.) with a large ductus, a large heart, and the symptom of exertional dyspnea. In ten patients, calculation of the internal diameter of the ductus was made; the values obtained ranged from 2.4 to 10.2 mm. Observed external diameters were from 5.5 to 18 mm. Even with allowance for variation in the thickness of the walls of the ducti, the calculated values seemed in general too small.

The regression (9) of observed external diameter on calculated internal diameter showed a significant association, $p = 0.02$ (Figure 1). Regression of external diameter on increase in percentage of oxygen saturation of pulmonary arterial over mixed venous blood (average of right atrial samples) also showed significant association, $p = 0.01$ (Figure 2). Regression of external diameter of the ductus on left-to-right

shunt showed also significant association, $p = <$ 0.02 (Figure 3). An association was thus shown between the observed diameter of the ductus and each of the following: theoretical internal diameter; volume of shunt through the ductus; and increase in oxygenation of pulmonary arterial blood. The correlation was by no means linear, there being considerable scatter about the regression line. When the theoretical internal diameter of the ducti was recalculated with variation in length considered (8), a somewhat closer association was found (Figure 4), $p = 0.001$, than with the orifice formula (5).
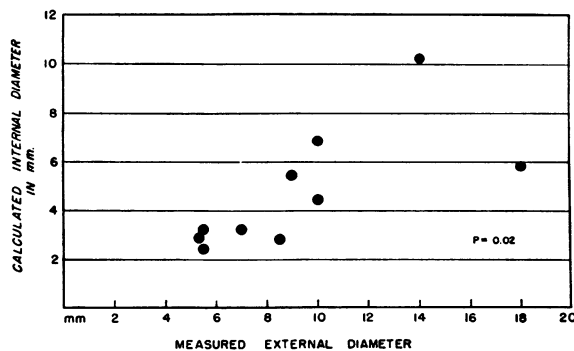

Fig. 1. Relation of Measured External Diameter to Calculated Internal Diameter in Ten Patients with Patent Ductus Arteriosus
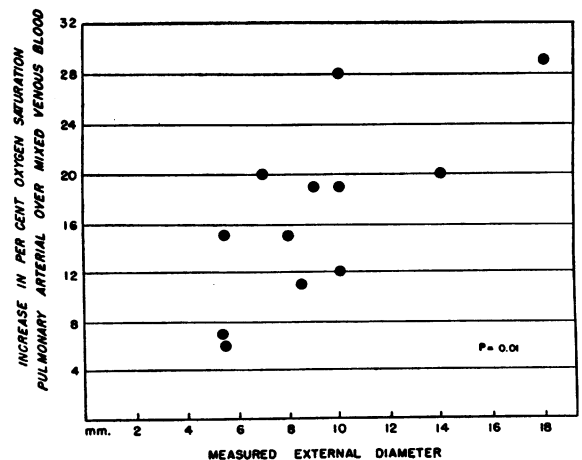

Fig. 2. Relation between Measured External Diameter and Increase in Oxygenation of Pulmonary Arterial Blood in Twelve Patients with Patent Ductus Arteriosus
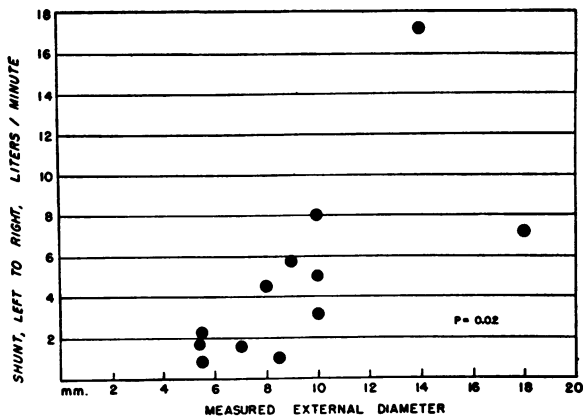
FIG. 3. RELATION BETWEEN MEASURED EXTERNAL DI-
AMETER AND LEFT-TO-RIGHT SHUNT IN TWELVE PATIENTS
WITH PATENT DUCTUS ARTERIOSUS

DISCUSSION

In 1950, Taylor, Pollack, Burchell, Clagett, and
Wood (10) published a study of the correlation
between flow through the ductus and its external
diameter measured at operation. No significant
correlation was found. However, these workers
did not calculate actual volume of flow, but rather
expressed flow as a percentage of left ventricular
output. Theoretically, one would expect the frac-
tion of left ventricular output passing through the
ductus to decrease with increase in body size and
cardiac output, assuming the cross sectional area
of the ductus to remain fixed, and a constant
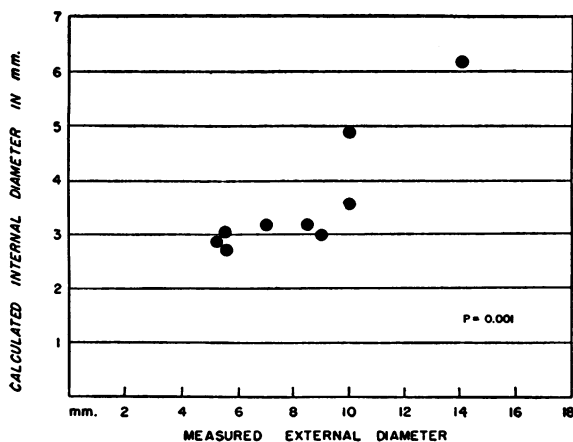aorta-pulmonary artery pressure gradient. These

workers did find the most constant correlation
between blood flow through the ductus arteriosus
and the product of the square of the radius of the
ductus and the square root of the aorta-pulmonary
artery pressure gradient. This corresponds to
the association we found between the calculated
internal diameter and the observed actual diameter.

Failure to find linear correlation between actual
size of the ductus and the hemodynamic data is
not surprising. There are many sources of er-
ror in such a study. The determination of the
degree of increased oxygenation of pulmonary ar-
terial blood is quite difficult, because there is poor
mixing of the two blood streams when samples are
taken so near the site of entrance of oxygenated
blood into the pulmonary artery. To reduce this
source of error, blood samples for pulmonary flow
calculation were taken from the distal right pul-
monary artery rather than the main pulmonary
artery. Eppinger, Burwell, and Gross (1) showed
that there is equal mixing of oxygenated blood
in both pulmonary arteries when there is an aortic-
pulmonary arterial shunt into the main pulmonary
artery of the dog. However, in humans, the
patent ductus arteriosus may be on occasion in-
serted considerably to the left of the midline of
the pulmonary bifurcation (1). In this event,
a sample from either pulmonary artery would give
an erroneous impression of the magnitude of the
shunt from the aorta. The degree of oxygenation
of pulmonary arterial blood is used in calculations
of flow through the ductus, which value is used
in turn in the calculation of the theoretical in-
ternal diameter of the ductus arteriosus. Any
error in this value would cause a corresponding
error in the two subsequent calculations. There
is a possibility of error in the patients whose
oxygen consumptions were assumed rather than
measured. Variations in the steady state are
a possible cause of error. In theory, one would
expect the calculated flow through the ductus to
be a better estimate of ductus size than the de-
gree of increase in oxygenation of pulmonary ar-
terial blood, since it includes the additional fac-
tor of the size of the subject. This was not seen
in the data. The calculated internal diameter from
the orifice formula (5) also failed to show a closer
association with measured ductus size, although
this determination includes the added element of
pressure gradient on either side of the shunt.

FIG. 4. RELATION BETWEEN MEASURED EXTERNAL DI-
AMETER AND CALCULATED INTERNAL DIAMETER IN NINE
PATIENTS WITH PATENT DUCTUS ARTERIOSUS, USING
THE POISEUILLE EQUATION

This suggests the possibility, as seems likely, that the ductus does not behave as a perfect orifice, and that there is considerable energy loss within it due to its length and possible tortuosity. The inclusion of the observed length in the formula for calculation of ductus diameter seemed to improve the association somewhat, but it is difficult to draw a conclusion from so small a sample.

Still another possible cause of difficulty in the above comparisons, relative to the measurement of ductus size, is that of variation in the thickness of the walls of the ducti, since the internal diameters were not measured. Since fluid viscosity enters into the formula for flow through short pipes (8), variations in blood viscosity are a potential source of error. Green, Lewis, Nickerson, and Heller (11) have shown that the effective viscosity of the blood decreases with increasing rates of flow, since blood is a non-homogeneous liquid. Thus variations in velocity of flow may add to the error of these calculations. Because of wave summation, systolic pressures in the femoral artery may exceed those in the aorta by as much as 20 mm. mercury (12). Thus the use of femoral arterial pressure as an estimate of aortic arch pressure in children may contribute some error.

SUMMARY

In twelve patients having a patent ductus arteriosus and subjected to ligation of the ductus at operation, a comparison was made between the observed diameter of the ductus arteriosus and certain hemodynamic data obtained by preoperative cardiac catheterization. Significant association was found between actual ductus diameter and each of the following: degree of increase in oxygenation of pulmonary arterial blood; calculated volume of blood flow through the ductus; and calculated internal diameter of the ductus. The failure of the calculated internal diameter to be a more accurate estimate of true ductus diameter than either the volume of flow through the ductus or the degree of increase in oxygenation of pulmonary arterial blood suggests that the ductus does not behave as a perfect orifice. Among the sources of error in these comparisons are difficulty in estimating the degree of oxygenation of pulmonary arterial blood; variations in ductus length and tortuosity; variations in steady state; variations in blood viscosity; variations in velocity of blood flow; discrepancy between femoral and aortic pressures; variations in thickness of the ductus walls.

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