Cardiac output
coronary blood flow
myocardial blood flow

pulmonary stenosis
radioactive microspheres
right ventricular hypertrophy

Coronary Reserve and Right Ventricular Function in Awake Newborn Lambs with Persistent Right Ventricular Hypertension

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Summary

Right ventricular function curves as measured by right ventricular stroke work were normal in all control lambs, whereas three of five lambs with banded pulmonary arteries had relatively flat curves. Left ventricular function was similarly normal in the control group as compared to a near zero slope function curve in the banded group. Regional myocardial blood flow to the septum and right and left ventricles was similar in control and banded lambs. At rest right ventricular coronary vascular resistance was lower in the banded than in the control group and decreased in both groups during both isoproterenol and dextran stress states. In general, both groups had a similar ratio of right to left ventricular oxygen supply to demand ratio. These results show first that there is minimal, if any, biventricular functional

reserve in lambs with persistent right ventricular hypertension, and second, that there is substantial coronary vascular reserve in both normal and banded groups.

Speculation

Although both right and left ventricular function are impaired in neonatal lambs with persistent right ventricular hypertension, the etiology is unclear. We have demonstrated right ventricular coronary vascular reserve in this group; however, we did not test for further reserve in the dextran stress state, and therefore cannot be certain that coronary blood flow was not maximal in the dextran state and hence ventricular function impaired by inadequate oxygen supply.

INTRODUCTION

During fetal life right and left ventricular systolic pressures are similar. Normally after birth right ventricular pressure decreases when pulmonary vascular resistance falls and the ductus arteriosus closes. However, right ventricular systolic hypertension may persist in a number of congenital cardiac defects and in neonatal pulmonary disease. In adult animals acute elevation of right ventricular systolic pressures to left ventricular levels is poorly tolerated (3,6,10), one explanation for which is inadequate right ventricular coronary blood flow (3,6,10,15,16). By contrast, the tolerance for increased right ventricular pressures in the early neonatal period may be due to greater coronary vascular reserve.

Although the normal newborn lamb heart has left ventricular function qualitatively similar to the adult (8), evidence of left ventricular coronary vascular reserve (8), a tolerance to hypoxia (15), and adequate response to positive inotropic agents (9), right ventricular functional reserve and coronary blood flow in normal newborn mammals and in those with right ventricular hypertension has not been investigated. While the fetal lamb has been shown to have impaired right ventricular function (11), we have previously shown that five to twelve week old lambs with persistent right ventricular hypertension created by pulmonary artery banding at two days of age have right ventricular hypertrophy, normal ventricular end diastolic pressures, and higher than normal right ventricular coronary blood flow both at rest and when stressed (2). We hypothesized that right ventricular function and coronary blood flow may be adequate in neonatal lambs early after pulmonary artery banding since elevated right ventricular afterload is a continuation of the prenatal state. Accordingly, we studied right ventricular functional reserve and coronary flow during the first 18 days of life in awake control and banded lambs at rest and during isoproterenol and dextran infusion stresses.

METHODS

Ten lambs were operated upon twenty-four to forty-eight hours after birth. They were premedicated with 5 mg of diazepam (Valium®), given 5 mg methohexital (Brevital®) intravenously, intubated with an endotracheal tube and ventilated by a volume controlled respirator with a mixture of 50% nitrous oxide and 50% oxygen containing 1% halothane. Under sterile conditions, a left thoracotomy was made in the fourth intercostal space and the ductus arteriosus ligated. Polyvinyl catheters (No. 5F) were placed in the internal mammary artery and vein, the left atrium via a pulmonary vein branch, the left pulmonary artery via a left upper lobe pulmonary artery branch, and the aorta through a purse string suture. A catheter (No. 5F end hole) was placed through a purse string in the outflow tract of the right ventricle. In five lambs we passed an umbilical tape around the main pulmonary artery and created a stenosis by tightening the tape. We used either a peak systolic right ventricular pressure of approximately two-thirds peak aortic pressure, the development of an arrhythmia, or a significant decrease in aortic pressure, whichever occurred first, as an end point in narrowing the pulmonary artery. The tape was then tied and the chest closed. Five control lambs had identical operative procedures but for the placement of the pulmonary artery tape. The pericardium was left open in all animals and a chest tube was used for several hours to insure full lung expansion. Catheters were brought out through percutaneous stab wounds in the back and were flushed daily with dilute heparinized saline.

All lambs were studied at five to eighteen days after birth. They were given only liquids the night prior to study. The next day they were loosely restrained on a table. Pressures were monitored with Statham P-230b pressure transducers with zero pressure set at the mid chest and recorded on an eight channel Beckman ink oscillograph. We used the radioactive microsphere method to measure the regional myocardial blood flow (4,5,7) and cardiac output (1). Filtered microspheres of 4-12 micron diameter (mean 7) labeled with ^{141}Ce , ^{85}Sr , ^{46}Sc , and 15 micron diameter ^{125}I labeled spheres were used. For each measurement approximately 4 to 5 x 10^5 microspheres suspended in two milliliters of 0.5% Tween were injected into the left atrium with 10cc of body temperature saline over 45 seconds. The method of preparation and injection of microspheres, and collection of arterial reference samples has been described (1,4).

Pressures, cardiac output, and myocardial blood flow were measured in each lamb at rest. Then isoproterenol infusion at 0.1 micrograms per kilogram per minute was begun; measurements were usually made after ten minutes, when pressure and heart rate had been stable for approximately five minutes. The isoproterenol infusion was then stopped, the lambs allowed to rest for ten to fifteen minutes until the heart rate and pressures had returned to pre isoproterenol infusion values. A slow infusion of Dextran 70 was then begun and continued until left atrial pressure increased 8 to 15 mmHg, or a total of 75cc per kilogram had been infused. Usually measurements were made at two left atrial pressures in this state. Because 15 micron diameter spheres may not measure transmural myocardial blood flow distribution as accurately as the filtered 4 to 12 micron diameter spheres and not as many can be given, the fifteen micron diameter iodine spheres were always given last.

We killed the lamb with intravenous barbiturate and removed the heart. The atrial septum was inspected for patency of the foramen ovale. The large coronary arteries, great vessels and fat were removed from the heart. The pulmonary veins and vena cava were cut close to the atrium, and the atrium were dissected from the ventricles and from each other. The free wall of the right ventricle was cut away from the left ventricle and both were dissected into four layers of approximately equal thickness. The myocardial layers were weighed, placed in vials, and the gamma radioactivity counted. After counting, the right ventricles of all lambs were dried at 110°C for 48 hours and reweighed. All animals were examined for pleural effusion, ascites, and hepatomegaly.

Traditionally, right ventricular coronary vascular resistance is calculated by dividing the difference between mean aortic and right atrial pressure by right ventricular coronary blood flow. Here, right ventricular coronary vascular resistance per unit weight was calculated using the pressure index (2,10) as the driving pressure; the pressure index is the integrated difference per minute between aortic and right ventricular pressures (10). The reason for using the pressure index instead of aortic pressure is because right ventricular chamber pressure may be transmitted into the ventricular wall and act as a Starling resistor on the coronary vascular bed.

We calculated an index of peak ventricular wall stress (τ) by multiplying peak ventricular pressure by the ratio of ventricular free wall weight to body weight ($\tau = P \times W_v/W_b$) (2). The adequacy of myocardial oxygen delivery was estimated by calculating the ratio of right to left ventricular oxygen delivery per unit peak systolic wall stress (2). This ratio removes variables common to both ventricles such as heart rate and arterial blood oxygen content, and accordingly, contains only right and left ventricular flow, peak systolic pressure and weight (from the wall stress calculation). The normalized distribu-

tion of flow within the sub regions of the right and left ventricle and septum was computed by dividing the flow per unit weight of each sub region by flow per unit weight of each region. This gives a measure of deviation from uniform flow for each region at each state studied.

RESULTS

The age at time of study, body weight, measured pressures and flows in the resting, isoproterenol and two dextran states for the five control and five banded lambs are given in Table 1. Control lamb number 1 was studied only in the resting state because of technical problems. The ratio of right ventricular dry to wet weight was similar in the control and banded groups, 0.149 ± 0.0057 and 0.152 ± 0.0055 (mean ± 1 standard deviations of mean) respectively. None of the lambs had a patent foramen ovale, pleural effusion or ascites. Banded lamb number 2 had an enlarged liver.

Figure 1 shows the ratio of right ventricular free wall weight to total body weight for both groups as a function of age. In general, the banded lambs tended to maintain a constant right ventricular weight to total body weight ratio over the thirteen day study period, and tended to be in the same range as a similar group of banded lambs studied at approximately sixty days of age (2). Conversely, this weight ratio decreased in the control group and approached the value seen at sixty days in normal lambs (2).

Right ventricular function as measured by right ventricular stroke work per kg body weight and mean right atrial pressure is depicted in Figure 2. Three studies were made in most lambs, the control and the two dextran infusion states. In general, the control group had normal right ventricular function curves as compared to the relatively flat right ventricular function curves in three of five banded lambs. Lamb number 2 in the banded group probably had right ventricular failure at rest because of the high right atrial pressure and because stroke work decreased as right atrial pressure increased.

Left ventricular function as measured by left ventricular stroke work per kg of body weight and mean left atrial pressure is shown in Figure 3. In general, the slope of the left ventricular function curve was near zero in banded lambs and positive in the control group. Lamb number 2 in the banded group had marked left ventricular failure at rest as evidenced by a resting left atrial pressure of 20 mmHg and low stroke work.

The regional distribution of myocardial blood flow to right ventricular free wall, septum and left ventricular free wall in the resting, isoproterenol and dextran states is shown in Figure 4. With the exception of banded lamb number 2, who was in biventricular failure, myocardial blood flow per gram to the septum and left ventricle was not very different in the two groups in the resting state. However, right ventricular flow was significantly higher at rest in the banded group ($p < 0.05$, by the Mann-Whitney U test). In the isoproterenol and dextran stress states, no appreciable differences in flow could be demonstrated except that the control group tended to have higher regional blood flows to all three regions in the isoproterenol state when compared to the regional blood flows in sixty day old control lambs (2).

Right ventricular free wall coronary vascular resistance is given in Figure 5 for the resting, isoproterenol and dextran states as a function of age. In the resting state, right ventricular coronary vascular resistance was lower in the banded group than in the control group. This difference was similar to that seen in the older lambs (2). The control lambs in the isoproterenol and dextran states tended to have a lower right ventricular coronary vascular resistance than the older lambs (significant at $p < 0.01$ for dextran by unpaired t test). Right ventricular coronary resistance in the banded lambs in the isoproterenol and dextran states was not different from values reported in older banded lambs (2).

The ratio of right to left ventricular oxygen delivery per unit peak systolic wall stress (2) is given in Figure 6 for the resting and two stress states as a function of age. In general, both the banded and control lambs tended to have a similar supply to demand ratio over the thirteen day study period. These values were lower than those previously found in an older banded group of lambs in all three study states (2).

Table II gives the mean and standard deviation of the mean for the transmural distribution of right ventricular coronary blood flow measured with the filtered 4-12 micron diameter spheres for the resting, isoproterenol and dextran states. In general, the mid wall of the right ventricle had a higher flow than both the subendocardial (inner) and subepicardial (outer) layers. There was no difference in transmural distribution between the banded and control group.

DISCUSSION

The results of this study are of interest from two aspects: First, the finding of reduced cardiac functional reserve in lambs with persistent right ventricular hypertension; and second, the finding of substantial coronary reserve in both control and banded lambs.

The limitations and criticisms of conventional ventricular function curves in intact experimental animals and man are applicable to this study. Specifically, increases in preload induced by volume infusion may also change afterload and possibly contractile state, thereby producing an influence on myocardial performance (cardiac output) in addition to that of preload or the Frank-Starling mechanism. The use of atrial pressure to estimate end diastolic fiber length or ventricular geometry assumes that diastolic compliance is similar between banded and unbanded groups and this may not be so. However, if ventricular compliance were decreased in the banded lambs, this would be an explanation for impaired right and/or left ventricular function. There are two additional potential sources of error. One is the possibility that the foramen ovale was patent resulting in an intra-atrial shunt. This would cause the right and left ventricular outputs to differ, and if the shunt was left to right cause an error in the microsphere cardiac output measurements. However, we did not identify a patent foramen ovale in any lamb. Further, left atrial pressure was higher than right in most states in all lambs. A second possible source of error was the use of the isoproterenol stress state prior to dextran infusion.

Our finding of impaired right ventricular function in the banded lambs in the early neonatal period is similar to that of Heymann and Rudolph (11) in normal fetal lambs in utero. However, the relatively normal right ventricular function curves in the control group suggests that impaired fetal right ventricular function is corrected during the neonatal period. Improvement in right ventricular functional reserve in normal lambs may in part be due to the fall in right ventricular pressure at birth. The impaired right ventricular function in the banded group in our study is in contrast to relatively normal right ventricular function in lambs studied 6 to 12 weeks after pulmonary artery banding (2). Comparison of right ventricular stroke work and right atrial pressures before and after dextran in our previous study (2) shows that

the older banded lambs had a slightly steeper right ventricular function curve than the older control lambs and than the control lambs in this study. The age at which measurements were made in the present study (4-17 days) is within the "injury phase" described by Meerson et. al. (17), whereas the older lambs (2) were in the compensated or stable hypertrophy period (17). This is consistent with the concept that ventricular function is impaired during the injury period of myocardial hypertrophy, but relatively normal during the stable state (17). Further, this suggests that maintenance of right ventricular afterload after birth is not just a continuance of the neonatal state, but an increased stress on the right ventricle. Closure of the foramen ovale after birth eliminates the neonatal right to left shunt, thereby increasing right ventricular stroke volume, an increase in right ventricular stress. This coupled with maintenance of right ventricular afterload in the post-natal period may produce a right ventricular stress state in excess of the fetal level. A final, although unlikely, possibility for the impaired ventricular function is that the biochemical stimulus for right ventricular growth was altered during the 24 or 48 hour period between birth and banding.

The finding that left ventricular function was impaired in the banded but not the control group suggests that persistent right ventricular hypertension in the early neonatal period has an effect on left ventricular function. It has been shown that pulmonary artery banding is associated with changes in left ventricular structure (13), late left ventricular hypertrophy (14), and increased left ventricular connective tissue (18). However, comparison of left ventricular stroke work and left atrial pressures before and after dextran in our previous study (2) shows that the older control and banded lambs had left ventricular function curves similar to the control lambs in this study. There is, however, no information on left ventricular biochemical or functional changes early after production of right ventricular hypertension.

The decrease in right ventricular weight to total body weight ratio in the control lambs in the first two and one-half weeks of life as compared to the maintenance of a near constant weight ratio in the banded lambs suggests that persistent right ventricular hypertension in the post natal period maintains stimulus to right ventricular growth not present in normal lambs. The difference in weight ratio between the two groups is not due to myocardial edema because the right ventricular wet to dry weight ratios were not different.

Right ventricular coronary flow per unit weight was lower than septal and left ventricular flow in the control group at rest, as is usually found in older animals (5,7,10,12). Conversely, right ventricular flow per unit weight was equal to or greater than septal and left ventricular flow in the banded lambs at rest. Further, resting right ventricular flow in banded lambs was significantly higher than in control lambs. This suggests an increase in oxygen demand per unit weight of right ventricular myocardium in the banded group, and is consistent with calculated higher values of right ventricular wall stress in the banded group (Table I). However, the ratio of right to left ventricular oxygen supply to demand ratio was similar in the control and banded groups and, in general, lower than that seen in banded older lambs (2). We have found the ratio of right to left ventricular oxygen supply to demand to be more sensitive to differences between banded and control groups than values for the right ventricle alone because the ratio method removes variability common to both ventricles such as heart rate, arterial blood oxygen content and the variability of the microsphere arterial reference sample method (2). During isoproterenol infusion regional flows to all three regions of the heart increased from resting levels in all control lambs and in 4 of 5 banded lambs, demonstrating resting coronary vascular reserve in both groups. Banded lamb number 2 was clearly in right ventricular failure, probably from too severe a constriction of the pulmonary artery, and had a very high resting right ventricular myocardial blood flow which did not change with stress. The remainder of the banded as well as the control lambs had a decrease in right ventricular coronary vascular resistance in both the isoproterenol and dextran stress states. This coupled with the similarity of the transmural distribution of right ventricular flow in both groups makes the possibility of impaired right ventricular function because of inadequate coronary blood flow seem unlikely. However, since we did not test for further right ventricular coronary vascular reserve in the dextran stress states we cannot be certain that coronary flow was not maximal and thus function impaired by inadequate oxygen supply.

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TABLE I. Hemodynamics in Control and Banded Lambs in Resting (R) Isoproterenol (I) and Two Dextran (D₁, D₂) States

	Age (days)	Body Weight (kg)	Hemoglobin (mg/dl)	Arterial PO ₂ (torr)				Heart Rate (beats/min)				Systolic LV Pressure (mmHg)				Systolic RV Pressure (mmHg)				Cardiac Index (ml·min ⁻¹ ·kg ⁻¹)				RV Wall Stress (torr x 10 ³)			
				R	I	D ₁	D ₂	R	I	D ₁	D ₂	R	I	D ₁	D ₂	R	I	D ₁	D ₂	R	I	D ₁	D ₂	R	I	D ₁	D ₂
Control																											
1	5	4.50	9.1	66	-	-	-	240	-	-	-	93	-	-	-	35	-	-	-	349	-	-	-	20.3	-	-	-
2	7	6.70	10.2	80	80	80	81	225	342	220	220	92	79	94	94	33	66	43	43	267	342	337	282	25.3	50.6	33.0	33.0
3	11	5.65	11.0	75	81	72	62	285	360	270	248	90	86	112	98	24	25	50	46	276	407	315	322	14.8	15.5	30.9	28.5
4	15	7.57	9.4	57	84	98	89	180	315	240	270	115	97	115	120	46	35	47	38	128	254	333	322	40.8	31.0	41.7	33.7
5	18	8.10	10.5	76	72	75	78	215	320	232	215	105	108	107	103	26	50	41	38	215	254	353	279	24.7	47.5	38.9	36.1
Banded																											
1	5	4.88	9.9	80	92	77	73	200	330	160	276	93	91	120	105	50	67	66	78	326	314	299	393	34.1	45.7	45.0	53.2
2	8	5.00	7.9	64	67	69	71	230	255	235	150	65	62	68	63	90	87	92	66	298	398	258	166	45.1	43.6	46.1	33.1
3	10	5.25	11.4	80	77	66	69	130	330	180	156	100	100	125	123	60	70	67	67	210	339	253	210	32.2	37.5	35.9	35.9
4	13	5.52	11.6	67	75	64	-	195	270	246	-	115	90	105	-	77	65	65	85	279	272	272	357	45.4	38.3	50.1	-
5	18	8.14	8.8	79	67	72	74	150	280	160	165	107	94	125	125	85	92	88	85	307	251	233	305	51.1	44.5	42.5	41.1

TABLE II. Right Ventricular Transmural Distribution of Blood Flow

	Control	Banded
Resting State		
I	0.995 ± 0.0300	0.953 ± 0.0616
M	1.123 ± 0.0286	1.127 ± 0.0448
O	1.009 ± 0.0720	0.960 ± 0.0289
Isoproterenol State		
I	0.913 ± 0.0436	0.929 ± 0.0754
M	1.224 ± 0.0301	1.130 ± 0.0424
O	0.951 ± 0.0370	0.981 ± 0.0494
Dextran State		
I	0.926 ± 0.0583	0.935 ± 0.0460
M	1.172 ± 0.0167	1.167 ± 0.0321
O	0.935 ± 0.0820	0.953 ± 0.0333

All values are mean $\pm$ 1 SDM and are obtained by dividing the flow per unit weight for the region (I is inner, M is mid and O is outer wall) by the flow per gram for the whole right ventricle (I + M + O).

Figure 1. The ratio of right ventricular free wall weight to body weight (w_{RV}/w_B) for control (•) and banded (○) lambs at their age when studied. The values on the right are for (mean $\pm$ 2 SDM) comparable groups at a mean age of 60 days (2).

Figure 2. Right ventricular stroke work (SW_{RV}) versus mean right atrial pressure (P_{RA}) for the control (•) and banded (○) lambs at rest and during dextran infusion. The numbers identify each lamb as per Table I.

Figure 3. Left ventricular stroke work (SW_{LV}) versus mean left atrial pressure (P_{LA}). Symbols and protocol per Figure 2.

Figure 4. Regional myocardial blood flow to free wall right ventricle (q_{RV}), septum (q_S) and free wall left ventricle (q_{LV}) for control (•) and banded (○) lambs during three study states. Values to right of each panel are (mean $\pm$ 2 SDM) flows for comparable groups at a mean age of 60 days (2) (t 0.05 $< p <$ 0.10, * $p <$ 0.05).

Figure 5. Right ventricular coronary vascular resistance for control (•) and banded lambs (○) at three states. Values on right of each panel are (mean $\pm$ 2SDM) resistance for comparable groups at a mean age of 60 days (2) (** $p <$ 0.01).

Figure 6. Estimate of right ventricular oxygen supply to demand ratio at age of study. Values on right of each panel are (mean $\pm$ 2SDM) ratios for comparable group at a mean age of 60 days (2) (* $p <$ 0.05).