Changes in posture are almost instantaneously associated with cardiovascular alterations, the nature of many of which has not yet been entirely elucidated. Several studies have demonstrated that the assumption of the erect from the recumbent posture is associated with changes in the position of the heart and diaphragm\(^1\) and a decline in cardiac output.\(^2\) Experimental investigations have shown that tilting dogs to 30 degrees, in either the head-up or the head-down position, causes a decrease in heart volume.\(^3\)

Likewise, the distribution of blood flow through the different segments of the lungs is affected by gravitational forces and, hence, by changes in posture. It was suggested by Lagerlöf and co-workers\(^4\) that with the body in the erect posture the blood flow would decrease to a great extent in the apical segments of the lungs as compared with the blood flow at the bases. Björkman\(^5\) demonstrated an increase in oxygen uptake in the dependent lung with the body in the lateral decubitus position, and he suggested that these changes are due to an increase in blood flow through the lowermost portions of the lung, as a result of the effects of gravitational forces on the distribution of the blood stream across the pulmonary circulation.

Since previous investigations have demonstrated that a preferential shunting of blood from the right lung and from the inferior vena cava occurs in the presence of atrial septal defects in the region of the fossa ovalis,\(^6\) \(^7\) investigations were carried out to evaluate the effects of passive tilting on the circulatory pressures and shunts in dogs with chronic atrial septal defects.

Determinations were carried out with the dogs in four positions: right decubitus, left decubitus, 45-degree head-up, and 45-degree head-down. Control values were obtained with the animals in the supine horizontal position.

**Methods**

Eleven mongrel dogs averaging 18.3 kg. (range, 14 to 22) in body weight were studied without thoracotomy between 3 weeks and 26 months after the creation of atrial septal defects. The defects, which were relatively large, had been produced by removing all tissue from the fossa ovalis and the major portion of the dorsal muscular septum and averaged 1.5 by 1.0 cm. in size.

Intravenous injections of sodium pentobarbital (26 mg. per kilogram of body weight) plus morphine sulphate (5 mg./Kg.) given subcutaneously were used for anesthesia. The animals were breathing room air at the time of these studies.

Four cardiac catheters (6 F. Lehman type) were introduced percutaneously via the external jugular veins and were manipulated under fluoroscopic control so that their intracardiac tips were positioned in the superior vena cava, inferior vena cava, right ventricle, and main pulmonary artery, respectively. In addition, in some animals a single-lumen catheter that opened into a rubber balloon\(^*\) 3 cm. proximal to its tip was used to produce acute partial obstruction of the main pulmonary artery as desired.

Central aortic pressure was recorded via a 60-cm. nylon catheter (inside diameter, 0.6 mm.; outside diameter 0.9 mm.) which was introduced through a thin-walled 19-gauge needle inserted percutaneously into one femoral artery. A 19-gauge needle was inserted into the opposite femoral artery for recording dilution curves.

Pressures transmitted through the catheter and needles were recorded by specially adapted strain-gauge manometers. Intravascular pressures, res...
pirations, and the electrocardiogram were recorded by means of a photokymographic assembly previously described. 9

The zero level for all manometers was set at midchest, and calibrations against a standardized aneroid manometer were made over the entire pressure range during and after each experiment. In each of the four body positions studied, the zero level of the hydraulic system 9 was referred to the same level on the external chest wall which was selected to be the midventral-dorsal point at the level of approximately the fifth to sixth interspace in the midaxillary line. In the head-up and head-down positions this was done by means of a "thistletube" attached to the chest and filled with saline solution so that the manicus was at midchest level. The zero-level pressure was then recorded by opening the hydraulic system of the manometers to this thistletube system while the animal was in the head-up, head-down, and supine positions, respectively.

The animals were held firmly in a specially designed dog rack by tying each of their legs and the sides of a wide canvas, which covered the ventral surface of each dog, to the sides of the rack. The rack was suspended on a centrally located transverse axis so that passive tilting to the 45-degree head-up or head-down position could be accomplished quickly and easily.

Indicator-dilution curves were recorded simultaneously from the femoral-artery and right-ventricular outflow tract by means of cuvettes 10 after injections of indocyanine green dye 11,12 into the venae cavae and the main pulmonary artery. Systemic and pulmonary blood flows as well as the magnitude of the left-to-right shunts were calculated from these curves as previously described. 13-15

The presence and magnitude of veno-arterial shunts were determined from dilution curves recorded from the femoral artery after injections of indicator into the venae cavae. 16 In part of the studies in which the effects of tilting on right-to-left shunts were studied subsequent to injections into the superior vena cava, it was necessary to produce these shunts with the animals in the control (horizontal) position by causing graded degrees of right ventricular hypertension by means of acute partial obstruction of the main pulmonary artery 17 consequent to distention of a catheter-tip balloon at this site.

The hearts of six animals were examined carefully at necropsy. The other animals are still living. In every instance the defect was located in the position formerly occupied by the membranous fossa ovalis and dorsal margin of muscular interatrial septum. A detailed description of the relation between the opening of the pulmonary veins and the venae cavae to the position of the defect in the atrial septum has been reported elsewhere. 18

Control determinations of circulatory pressures and shunts were carried out in every instance with the animal in the control (horizontal) position immediately prior to and after tilting. The control values given are the average of the results obtained during the horizontal positions before and after each tilting.

The larger contribution of blood flow from the inferior than from the superior vena cava to the right-to-left shunt, as well as the preferential shunting of blood from the right lung across the atrial septal defect in these animals, has been reported previously. 18

A small veno-arterial shunt was detected after superior caval injections in only three animals in the control or horizontal position. In order to obtain a demonstrable right-to-left shunt after injections of indicator into this site, graded degrees of right ventricular hypertension were produced in six animals by means of partial obstruction of the main pulmonary artery by inflating a catheter-tip balloon at this site.

Results

The effects of changes in body position on blood pressures and on the magnitude of the right-to-left shunts in one dog with chronic atrial septal defect are illustrated in figure 1. In each of the body positions studied, injections of indicator into both the superior and inferior venae cavae were carried out with recording of the resulting dilution curves from the femoral artery. It is evident from these dilution curves that, subsequent to injections of indicator into the inferior vena cava, the 45-degree head-up tilt was associated with an increase in the magnitude of the right-to-left shunt. Opposite effects were obtained during the 45-degree head-down tilt. However, these effects on the magnitude of the right-to-left shunt were not demonstrable after injections of indicator into the superior vena cava in spite of identical alterations in circulatory pressures.

45-DEGREE HEAD-UP TILT

The results comprise 17 experiments carried out in 11 animals with an interval of one to several months between the studies.

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The average mean right atrial pressure in the horizontal position was 4.6 mm. of mercury (range, 1 to 7). Right ventricular systolic pressure averaged 46 mm. of mercury (range, 20 to 95), and mean aortic pressure averaged 125 mm. of mercury (range, 96 to 160).

In every instance the indicator was injected into the inferior vena cava prior to, during, and after tilting. Subsequently, on nine occasions these determinations were performed after injections into the superior vena cava.

The values obtained for right-to-left shunts after injections of indicator into the inferior vena cava in the control (supine) positions averaged 20.2 per cent (range, 1 to 46) of the systemic blood flow (fig. 2, left panel). On one occasion (dog 10), due to the severe degree of obstruction of the main pulmonary artery, an extremely large right-to-left shunt had developed and, therefore, this result is not computed in this series due to the relatively large error in quantitating right-to-left shunts of this magnitude. Measurements of right-to-left shunts subsequent to injections into the superior vena cava during the control situation uniformly showed smaller values than those for injections into the inferior vena cava, the average value of 7.5 per cent (range, 0 to 23) of the systemic blood flow amounting to about a third of the inferior caval figures (fig. 2, middle panel).

Passive head-up tilting of these animals was followed immediately by a fall in the mean right atrial pressure of 3.7 mm. of mercury (range, 0.5 to —6.5) and a rise in mean aortic pressure of 10 mm. of mercury (range, —5 to 30). During the tilt, mean right atrial pressure averaged 0.3 mm. of mercury (range, —6 to 4.5) and the mean aortic pressure, 135 mm. of mercury (range, 100 to 165). The relation between the changes in the magnitude of the right-to-left shunts across the defects and the alterations in circulatory pressures associated with this body position is shown in figure 3.

Tilting these animals head-up was associated with an increase in the heart rate in 12 of the 17 experiments. The average increase in the experiments amounts to 10 beats per minute (range, —6 to 35) which represents a 10 per cent increase over the control values. The average respiratory rates of 14 breaths per minute (horizontal position) and 13 breaths per minute (45-degree head-up position) were not significantly affected by this posture. The range of changes in the respiratory rate associated with the 45-degree head-up position varied from —5 to 8 breaths per minute in individual animals.

In every instance except two, during the 45-degree head-up tilt, the magnitude of the right-to-left shunt increased as determined after injections of indicator into the inferior vena cava. In the 16 experiments the average
increase in the right-to-left shunt was 6 per cent (range, —18 to 15) of the systemic blood flow, as compared with the control (horizontal) determinations ($P > 0.001$). In the 14 determinations in which an increase in the magnitude of the right-to-left shunt occurred, this increase averaged 8.2 per cent (range, 2 to 15) of the systemic flow (fig. 2, left panel). In contrast, no systematic change was demonstrable for the right-to-left shunt as detected after injections into the superior vena cava (fig. 2, middle panel).

Tilting these animals to the head-up position was not associated with systemic effects on the magnitude of the left-to-right shunts, as determined by indicator-dilution techniques (fig. 2, right panel).

After the animals were tilted back to the horizontal position, circulatory pressures, heart rate, and the magnitude of the shunts returned rapidly to the range of values obtained prior to tilting.

45-DEGREE HEAD-DOWN TILT

Similar studies of the effects on blood pressures and shunts were obtained during head-down tilt performed in 11 dogs. These studies comprise 17 experiments carried out in association with contiguous observations of the effects of the 45-degree head-up tilting.

Control determinations of circulatory pressures and shunts in dogs in the horizontal position prior to and subsequent to tilting were similar to the control values obtained for the head-up tilt.

The right-to-left shunts were determined after injections of indicator into the inferior vena cava in all 19 of the experiments and on eight occasions determinations were made after injection into the superior vena cava. In the horizontal position, the right-to-left
shunts after injection into the inferior vena cava averaged 19.1 per cent (range, 0 to 49) as compared to the average value of 9.3 per cent (range, 0 to 30) of the systemic blood flow obtained after injection into the superior vena cava.

An increase in mean right atrial pressure was observed in most of the animals during the head-down position, which averaged 1.0 mm. of mercury (range, -2 to 5). During this posture, mean right atrial pressures averaged 4.5 mm. of mercury (range, 1 to 9). In every instance this body position was associated with a decrease in mean aortic pressure which averaged 15.3 mm. of mercury (range, -1 to -34) as compared with control (horizontal) determinations. During the horizontal posture, the mean aortic pressure averaged 132 mm. of mercury (range, 70 to 155). These alterations in blood pressures were opposite to those obtained during the 45-degree head-up tilt.

The respiratory rate was consistently increased during the head-down tilt by an average of 4 breaths per minute (range, 1 to 8) over the control values obtained during the horizontal position. The control respiratory rate averaged 14 breaths per minute (range, 4 to 28). There was no systematic change in the heart rate during this body position.

The 45-degree head-down position was associated with a decline in the magnitude of the veno-arterial shunts as determined after injections into the inferior vena cava (fig. 2, left panel) in 10 of 16 experiments. The average value for the right-to-left shunt dur-
Effects of passive changes in posture from supine to lateral decubitus positions on the magnitude of pulmonary blood flow and left-to-right shunts across atrial septal defects in six anesthetized, closed-chest dogs breathing room air. Average values obtained during the supine position before and after each rotation into the decubitus position are plotted on the ordinate against the values obtained in the decubitus position on the abscissa. The diagonal line represents the locus of identical values for the supine and lateral decubitus positions. Note that the right lateral decubitus position was invariably associated with an increase in pulmonary blood flow in relation to values obtained when supine (left panel), whereas no systematic change was observed during the left lateral decubitus position. Similarly, the right lateral decubitus position was associated with a small, but consistent, increase in the magnitude of the left-to-right shunt, whereas no systematic effect was obtained in association with the left lateral decubitus position.

No appreciable changes in circulatory pressures were demonstrable during either the right or the left lateral decubitus position.

The effects on pulmonary blood flow and on the magnitude of the left-to-right shunts are shown in figure 4. In every instance, the right lateral decubitus position was associated with a significant increase in pulmonary blood flow and an increase in the magnitude of the left-to-right shunts as calculated by indicator-dilution techniques.

Control determinations showed pulmonary blood flow to average 5.7 L. per minute (range, 4.3 to 8.0). The average increase in pulmonary blood flow during the right lateral decubitus position was 0.8 L. per minute (range, 0.4 to 1.2). Average values for pulmonary blood flow during the control (horizontal) positions for left lateral decubitus position were similar to those obtained during the control determinations for the right lateral decubitus position. However, changing the position of the animals to left lateral decubitus position was not associated with a demonstrable systematic effect on pulmonary blood flow (fig. 4, left panel).

Similar changes expressed as percentages of the pulmonary blood flow were seen in the magnitude of the left-to-right shunts as determined by indicator-dilution techniques during the 45-degree head-down tilt (fig. 2, right panel).

LATERAL DECUBITUS POSITIONS

The effects on circulatory pressures and on the magnitude of the left-to-right shunts and pulmonary blood flow were determined in six animals in the horizontal (supine) position and subsequently when the animals were rotated to the right lateral or the left lateral decubitus positions.

During the head-down position was 16.1 per cent (range, 0 to 49) of the systemic blood flow, which represented an average decrease of 3 per cent (range, —16 to 8) of the systemic flow ($P < 0.05$). On three occasions it was unchanged. It is of note that on two occasions a small veno-arterial shunt demonstrable after injections into the inferior vena cava when the animals were in the horizontal position disappeared during tilting to the head-down position. In contrast, no systematic changes in the right-to-left shunt were obtained subsequent to injection of indicator into the superior vena cava (fig. 2, middle panel) during this body position. During the head-down tilt this shunt averaged 10.7 per cent (range, 0 to 36) of the systemic blood flow.
during the supine position. The left lateral decubitus position, however, was not associated with a demonstrable systematic change in the magnitude of the left-to-right shunt.

**Discussion**

It is well known that complex circulatory adjustments result from changes in body position from the supine to head-up and head-down tilt positions, and it would not be unexpected if these circulatory alterations were associated with changes in the degree of shunting across an atrial septal defect.

Under experimental conditions head-down tilting results in an increased right ventricular inflow, while effects in the opposite direction occur during head-up tilting. In animals with intact cardiac septa, decrease in rate of inflow caused by hemorrhage has been demonstrated to cause a greater reduction in atrial pressures in the left atrium than in the right atrium. Obviously, a reduction in the pressure gradient across the interatrial septum occurs under these circumstances, and if an atrial septal defect had been present, this would alter the direction and magnitude of the shunts during some phases of the cardiac cycle.

In the 11 animals in this series, changes in atrial inflow may be inferred from the alterations observed in right atrial pressures associated with passive tilting. During the 45-degree head-up tilt the mean right atrial pressure was consistently lowered, possibly due to lesser degree of right atrial inflow. The elevation in mean right atrial pressure during the 45-degree head-down tilt probably is related to an increased rate of inflow.

The erect posture has been demonstrated to produce alterations in peripheral vascular resistance. In fact, in this series of experiments, a consistent elevation in mean aortic pressure occurred, probably as a result of vasoconstriction, consequent to the reduction in venous return, right atrial pressure and right ventricular output. Under these circumstances a fall in cardiac output and a decrease in heart volume would be anticipated during the 45-degree head-up tilt.

The most striking feature of the observations reported herein is the dissimilar results which were obtained in the right-to-left shunts as detected after injections of indicator into the superior and inferior vena cavae, in spite of the identical alterations in circulatory pressures which occurred during the two sets of determinations. The increase in right-to-left shunt in the head-up position is of particular interest in view of the fact that during head-up tilt, the mean right atrial pressure was consistently decreased; probably venous return to the right side of the heart also was decreased and hence the filling pressure was reduced. These changes would be expected to decrease the magnitude of a right-to-left shunt unless accompanied by concomitant changes of equivalent magnitude on the left side of the heart. Similar comments pertain to the decrease in right-to-left shunt observed during head-down tilting in spite of the increase in right atrial pressure which occurred under this circumstance.

Similar results have been reported by Wright and co-workers concerning the effects of changes in body position on the respiratory and circulatory variables in a patient with Ebstein's malformation of the tricuspid valve associated with an atrial septal defect. In this patient considerable decrease in arterial oxygen saturation was observed when he was tilted from the horizontal to the head-up position.

The cause of these alterations in the right-to-left shunts during changes in posture have not been elucidated as yet, but apparently they are not related to alterations in any of the measured physiological variables. It appears probable that these changes may be the result of alterations in the anatomical relationship between the right atrial ostia of the veins cavae and the position of the defect in the atrial septum.

The resting position of the diaphragm has been demonstrated to be consistently lower during the erect posture than during the horizontal position. It seems possible that the descent of the diaphragm and the heart during the 45-degree head-up tilt results in a
closer relationship between the ostium of the inferior vena cava and the position of the defect in the atrial septum than exists during the horizontal position; hence, an increase occurs in the right-to-left shunt from the inferior vena cava across the atrial septal defect when in the upright position and possibly the opposite effects develop in the head-down tilt.

If this were the explanation, the opposite or no effect in the right-to-left shunting of superior caval blood would be expected. In actuality, no effect on the shunt was detected after injections into the superior vena cava. Such postulated alterations in the anatomical relationships of the inferior caval ostium and the atrial septal defect with change in posture would not be expected to produce alterations in the left-to-right shunts and none were observed.

Determinations of oxygen uptake have been accepted generally as an index of distribution of blood flow through the lungs, which is seldom uniform through the different segments of both lungs in the supine position. Changes in posture from the supine to the lateral decubitus result in an increase in oxygen uptake in the dependent lung. The main cause for this increase in oxygen uptake has been considered to be an increase in blood flow through the dependent lung as a result of gravitational forces on the distribution of the blood stream across the pulmonary circulation. Similar results were obtained when labeled radioactive material was used for such determinations.

A larger contribution of the right lung to the left-to-right shunt across atrial septal defects of the secundum type has been shown by means of indicator-dilution techniques. Therefore, if the right lateral position results in increased blood flow through the right lung, the increase in degree of the left-to-right shunting which was observed in relation to values obtained in supine position would not be unexpected and would be responsible for the consistent increase in pulmonary blood flow which was obtained in this position. Likewise, increased blood flow through the dependent left lung is expected to occur during the left lateral decubitus position; however, this position would not be expected to increase, but, perhaps, on the contrary, to decrease the flow of blood across the atrial septal defect due to the anatomical relation between the opening of the left pulmonary veins and the position of the defect in the atrial septum. In fact, in these animals no systematic changes in pulmonary blood flow or the magnitude of the left-to-right shunts were demonstrable during the left lateral decubitus position.

These results are consistent with previous observations in these dogs which demonstrated that increasing blood flow across the right lung, as achieved by total occlusion of the left main pulmonary artery, resulted in an increase in the magnitude of the left-to-right shunts across the septal defect, whereas increasing blood flow across the left lung, as a result of obstruction of the right pulmonary artery, did not produce a systematic effect on the magnitude of the left-to-right shunts.

Summary
The effects of passive tilting on the circulatory pressures and on the magnitude of shunts across chronic atrial septal defects were studied in 11 dogs with closed chests. These determinations were performed with the dogs in four positions: 45-degree head-up, 45-degree head-down, right lateral decubitus, and left lateral decubitus. Control values were obtained with the animals in the supine horizontal position.

The 45-degree head-up tilt position was associated with an increase in the magnitude of the right-to-left shunt detected after injections of indicator into the inferior vena cava, while change from supine to the 45-degree head-down tilt resulted in a decrease or disappearance of a pre-existing right-to-left shunt detected after similar injections. These effects on the right-to-left shunt were not demonstrable after injections of indicator into the superior vena cava, either during the head-up or head-down tilt, in spite of identical alterations in circulatory pressures. A significant interanimal correlation between
ATRIAL SEPTAL DEFECTS

the magnitude of the changes in systemic or right atrial pressures and the magnitude of the changes in right-to-left shunts could not be demonstrated. Passive changes in posture from supine to 45-degree head-up or head-down positions were not associated with demonstrable systematic effects on the magnitude of the left-to-right shunts. It is postulated that the descent of the heart and diaphragm during the head-up tilt results in a closer anatomical relation between the ostium of the inferior vena cava and the defect in the atrial septum and consequently an increase in the preferential shunting of inferior caval blood through this defect. In these animals, changing the body position from the supine to the right lateral decubitus position was consistently associated with an increase in the magnitude of the left-to-right shunts across the atrial septal defect and an increase in pulmonary blood flow. Since these animals have preferential shunting of blood from the right lung in the left-to-right direction, it is believed that the increase in blood flow through the dependent right lung is responsible for the observed increase in the left-to-right shunt. The left lateral decubitus position was not associated with appreciable effects on pulmonary blood flow or left-to-right shunting of blood across the atrial septal defect.

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