An Evaluation of Wedge Pressures in Dogs under Conditions of Normal and Elevated Pulmonary Vascular Pressures

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Fifty-six combined right and left heart catheterizations in normal dogs and dogs with experimental mitral stenosis failed to show a significant positive correlation between pulmonary artery wedge pressure and pulmonary vein pressure when the latter was below approximately 17 mm. Hg. Evidence is presented which suggests that the wedged catheter outlets are totally occluded in many instances in the dog. Pulmonary vein wedge pressure reflected a pressure nearer the pulmonary artery pressure than the expected capillary pressure. One instance of mitral regurgitation revealed large pulmonary vein and pulmonary artery wedge pulse pressures.

HELLEMS and colleagues have described a method of estimating pulmonary capillary pressure in the dog by means of a cardiac catheter wedged into either a small pulmonary artery or a small pulmonary vein. This method has subsequently been used extensively in the human during catheterization of the right side of the heart. The technic has not, however, been adequately tested in the intact animal over a wide range of pulmonary vascular pressures. An unusual opportunity to evaluate the wedge pressure presented itself during the study of experimental mitral stenosis as described by Ferrin, Adams, and Baronofsky. It is the purpose of this paper to determine whether the wedge pressure adequately and practically reflects a wide range of pulmonary capillary pressures under conditions simulating cardiac catheterization in the human. This is particularly pertinent in view of numerous studies of pulmonary hemodynamics based largely on the wedge pressure which are appearing in the literature.

METHODS

Mongrel dogs were anesthetized with intravenous pentobarbital sodium, 33 mg. per kilogram, and subjected to combined right and left heart catheterization, as described by Haddy, Campbell, Adams, and Visscher, approximately two weeks before and again two weeks after the production of experimental mitral stenosis. In 44 instances a number 8 Goodale-Lubin cardiac catheter with three terminal orifices ("birds eye tip") and in 12 instances a number 8 Cournand catheter with a single terminal orifice was wedged into a small pulmonary artery. A number 10 radio-opaque ureteral catheter with three terminal orifices ("whistle tip") was introduced one or two centimeters into a pulmonary vein. After recording simultaneous pressures, the catheter on the right side of the heart was withdrawn into the main pulmonary artery and the catheter on the left side of the heart was wedged into a small pulmonary vein. Pressures were again recorded simultaneously with standard resistance wire pressure transducers (Statham strain gages). Zeros were determined by exposing the strain gages to atmospheric pressure at the level of the tips of the catheters as determined fluoroscopically. In addition, the vertical distance between the catheter tips was noted and a suitable correction made for the hydrostatic head between them. Intrathoracic pressure was also measured. Integrated mean pulmonary artery, pulmonary vein, pulmonary artery wedge, pulmonary vein wedge and intrathoracic pressures were measured with a compensating polar planimeter, and all pressures recorded in this paper are expressed in relation to intrathoracic pressure as zero. Indices of a well-wedged catheter were taken to...
be its peripheral position in the lung field, snapping back of the tip of the catheter upon withdrawal and reduction of the pulmonary artery wedge pulse pressure when compared to the pulmonary artery pulse pressure. Inability to withdraw blood from the catheter wedged in the pulmonary artery was a uniform finding. In only one animal, a dog with a very high pulmonary vein pressure due to mitral regurgitation, was blood successfully withdrawn. It appeared to be well oxygenated.

**RESULTS**

Figure 1 presents the results of 56 simultaneous measurements of pulmonary artery wedge and pulmonary vein pressures. Pulmonary vein pressures ranged from 4.5 to 28.4 mm. Hg. A statistically significant correlation between pulmonary artery wedge and pulmonary vein pressure could not be demonstrated, \( x^2 = 361, P < .01 \) according to Fisher's method.\(^*\) The lack of correlation was especially apparent when pulmonary vein pressures below about 17 mm. Hg were encountered.

Pulmonary artery wedge pressures considerably higher than the corresponding vein pressures were often recorded. In 11 instances the wedge pressure was less than pulmonary vein pressure. In one instance a pressure was recorded from a well wedged catheter which was 13.8 mm. Hg in excess of pulmonary artery pressure. In 8 of 12 normal dogs gentle flushing of the wedged Courand catheter with a 2 to 3 cc. volume of saline, 5 per cent glucose or Ringer's solution caused the wedge pressure to vary at random without similar changes in the pulmonary vein pressure. The pressure recorded after each flush was sustained until the next flushing. Variations in wedge pressure as large as 28 mm. Hg were produced in this manner, the pressure sometimes exceeding pulmonary artery pressure and sometimes falling below pulmonary vein pressure.

To evaluate this finding further, additional experiments were performed in normal dogs employing a Courand catheter wedged into a pulmonary artery. A T-tube was inserted between the catheter and strain gage so that varying amounts of positive or negative pressure could be momentarily applied to the catheter. In 8 of 14 wedge positions, the wedge pressure value was different following each application of pressure. Figure 2 is a reproduction of a record of such an experiment. It will be noted that the wedge pressure varied between 13 and 28 mm. Hg and that at no time did it approach the value in the pulmonary vein which was 7 mm. Hg.

Pulmonary artery wedge pressure reflected the pulmonary vein pressure more accurately when pressures in the latter were in excess of 17 mm. Hg. \( x^2 \) for these animals equaled 8.0, \( P \) lying between 0.5 and 0.3.

\* \( x = \sqrt{\frac{x^2}{m}} \); where \( m \) is the number expected and \( m + x \) the number observed. \( P \) values between .1 and .3 indicate a high degree of correlation and values below .02 strongly indicate absence of correlation.
Figure 3 presents the observed pulmonary artery and pulmonary vein wedge pressures from 40 separate catheterizations. The integrated mean pulmonary artery pressures ranged from 14.3 to 38.1 mm. Hg. Of particular interest was the observation that in nine instances the pulmonary vein wedge pressure was higher than the recorded pulmonary artery pressure. Indeed, in 25 of 40 instances, the pulmonary vein wedge pressure was within 25 per cent of the pulmonary artery pressure. This strongly suggests that the pulmonary vein wedge pressure did not reflect capillary pressure in the majority of cases. That the vein wedge pressure also did not accurately reflect pulmonary artery pressure was demonstrated by a $\chi^2$ of 86.6 with $P < .01$ when all 40 cases were considered. This lack of correlation was mainly due to a large number of pulmonary vein wedge pressures which were considerably below pulmonary artery pressures when pulmonary hypertension was absent.

When the pulmonary artery pressure was definitely elevated, the correlation between pulmonary artery and pulmonary vein wedge pressures became significant. All 10 animals with integrated mean pulmonary artery pressures above 26 mm. Hg had pulmonary vein wedge pressures within 25% of the former.

One animal catheterized 20 days following attempted creation of an experimental mitral stenosis was found to have an extremely high pulmonary vein pulse pressure, which suggested mitral insufficiency. Simultaneous recording of pulmonary artery wedge and pulmonary vein pressures revealed the records reproduced in figure 4. Of particular interest are the wide pulse pressures in both locations, the 0.04 second delay in the maximal pulmonary artery wedge pressure peak, when compared to the maximal peak in the pulmonary vein and the apparent gradient from pulmonary vein to pulmonary artery wedge during ventricular systole. This was the only preparation from which blood was successfully withdrawn from the wedged pulmonary artery catheter. The blood appeared well oxygenated. The animal was sacrificed while in extremis from pulmonary edema 11 days after catheterization and was found to have a normal sized mitral ring with a large tear in the aortic leaflet of the mitral valve.

**Fig. 3.** Relation of pulmonary vein wedge pressure to pulmonary artery pressure simultaneously measured during 40 catheterizations in normal dogs and dogs with experimental mitral stenosis.

**Fig. 4.** Record of simultaneous measurement of pulmonary artery wedge and pulmonary vein pressures in a dog with mitral insufficiency. Note the wide pulse pressures in both locations and the 0.04 second delay in the maximal pulmonary artery wedge pressure peak.

**DISCUSSION**

The observation that in the absence of marked pulmonary vein hypertension, the pulmonary artery wedge pressure varies from above pulmonary artery pressure to below pulmonary vein pressure indicates that the
wedge pressure need not reflect capillary pressure as suggested by Ilellems and co-workers or left atrial pressure as suggested by Dow and Gorlin. The absence of a correlation is even more significant in the light of the fact that the pulmonary vein pressure was a known factor in these experiments, a condition not obtained when catheterizing only the right heart. This lack of correlation still remained even though the catheter was often rewedged in an attempt to obtain a wedge pressure nearer the known pulmonary vein pressure.

It is likely that in the process of "wedging," at least in the dog, the catheter outlets are totally occluded in many instances. The pressures recorded when the catheter is retracted until blood can be withdrawn are pulmonary arterial pressure when the catheter is inserted in the artery and pulmonary vein pressure in the opposite case. Since the pressures reached at equilibrium after raising and lowering the intracatheter pressure when the catheter is wedged, are ordinarily not identical, one cannot determine pressure by a "null point" method. Even the range of pressures so determined does not agree with measured venous pressures.

It seems unlikely that the effect of blood velocity on the catheters was an important factor in these experiments. In a model, it was determined that a blood velocity of 80 cm. per second flowing into the tip of the type catheter used in the pulmonary vein would be necessary to raise the pressure 2 mm. Hg above true lateral pressure. Similar experiments with the catheters used in the pulmonary artery demonstrated that a blood velocity of approximately 150 cm. per second flowing past the catheter tip would be necessary to reduce the recorded pressure 2 mm. Hg below true lateral pressure. Velocities above these magnitudes are unlikely in the pulmonary tree.

The significant correlation between wedge pressure and observed venous pressure under conditions of pulmonary vein hypertension would suggest that the wedge pressure more accurately reflects pulmonary vein pressure when the lung vessels are distended. It should, however, be pointed out that the pulmonary artery to pulmonary vein pressure gradient becomes very small when the pulmonary vein pressure is elevated by experimental mitral stenosis. Elevation of pulmonary vein pressure in the dog by other methods also narrows the gradient. The pulmonary artery to pulmonary vein pressure gradient ranged from 3 to 10 mm. Hg in the eight animals in question. In the presence of gradients of this magnitude, the pulmonary artery wedge pressure would necessarily be relatively close to pulmonary vein pressure even if collateral channels from other pulmonary arteries were present. It was also observed that the pulmonary vein wedge pressure reflected pulmonary artery pressure more accurately when the latter was elevated. This may also only be an apparent accuracy due to narrowing of the gradient when pulmonary vein and artery pressures are elevated by experimental mitral stenosis.

Even though the wedge pressure were assumed to be accurate under conditions of pulmonary vein hypertension, its use would still be of questionable value during catheterization of the right heart alone. During right heart catheterization, the pulmonary vein pressure remains unknown; and, therefore, the circumstances under which the wedge pressure would be dependable would also remain unknown.

It is clear from the observations presented that a catheter wedged in a pulmonary vein need not reflect capillary pressure. Since the pulmonary vein wedge pressures were distributed on either side of the pulmonary artery pressures, it seems proper to conclude that in the majority of instances pressures nearer those in the pulmonary arteries were reflected. These findings are in agreement with those of Weissel and colleagues who found in five human cases of atrial septal defect that the mean pressure recorded from a catheter wedged in a pulmonary vein exceeded considerably the mean pressure in the nonobstructed pulmonary vein. In this regard, the recent demonstration of large shunts between the pulmonary artery and vein in both dog and human lungs is of interest.

The case of mitral insufficiency corroborates the view of others, namely, that the pulmonary artery wedge pressure may be of value in indicating incompetence of the mitral valve. Ankeney has stated that retrograde transmission
of phasic pressure changes from the left atrium to the wedged pulmonary artery catheter would be a hemodynamic impossibility unless a pressure gradient existed in that direction. It should be noted in figure 4 that the maximal pressure peaks in the pulmonary vein appear to be in excess of those recorded from the wedged catheter. Thus during systole there may be a reversed pressure gradient in mitral insufficiency. We believe that a conclusion on this score is impossible until instrumental artefacts are more completely eliminated than is the case with the catheterization technics that we and others are currently using.

CONCLUSIONS

1. Fifty-six combined right and left heart catheterizations in normal dogs and dogs with experimental mitral stenosis revealed pulmonary vein pressures ranging from 4.5 to 28.4 mm. Hg. A significant positive correlation between pulmonary artery wedge pressure and pulmonary vein pressure was absent when the latter was low. Under the conditions studied, a significant correlation was observed between the two when the pulmonary vein pressure was elevated above approximately 17 mm. Hg.

2. In 8 of 12 instances, flushing through the catheter, and in 8 of 14 instances application of momentary positive or negative pressure to the catheter wedged in the pulmonary artery caused the pressure recorded to vary at random. These findings, together with the inability to withdraw blood from the wedged catheter, suggest that the wedged catheter outlets are totally occluded in many instances in the dog.

3. Pulmonary vein wedge pressure reflected a pressure nearer the pulmonary artery pressure than the expected capillary pressure.

4. One instance of mitral regurgitation revealed large pulmonary vein and pulmonary artery wedge pulse pressures.

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