LIMITATIONS OF THE WEDGE PRESSURE MEASUREMENT

by

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ABSTRACT

The pulmonary artery wedge pressure, obtained with a balloon catheter wedged in a branch of the pulmonary artery, is used in the clinical cardiovascular setting as an estimate of left atrial pressure (LAP). The theory behind this indirect LAP, which is that LAP is reflected back through the pulmonary circulation to the blocked point, where pressure is measured, is too simplistic and generally unsupported. The literature concerning the relationship includes studies with a variety of conditions and sample populations, and thus, contains seemingly conflicting reports on the reliability of PAW as an indication of LAP. For this reason, the problem was approached in an engineering fashion, and a model of the system was developed. The model, although simple, is valuable as an educational tool to better understand the system itself, and as a means of integrating the results of studies in the literature.

ACKNOWLEDGEMENTS

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INTRODUCTION

The measurement of blood pressures within cavities of the heart is often desirable in the clinical cardiovascular setting. These values may be used for diagnosis of heart disease by comparison with accepted normal values. Right heart pressures are readily obtained by passing a catheter through the venous system. The measurement is actually obtained by coupling the catheter to an external pressure transducer and recorder, to display the pressure waveform. Left heart pressures are especially important, since the left ventricle pumps blood to the body, but unfortunately, these are more difficult to obtain than right heart pressures. Direct measurements in the left heart can be achieved through catheterization by either a transeptal route (right to left heart through punctured septum), or an aortic route.[1] Both methods have disadvantages. Puncture of the septum is traumatic, and travelling through the aorta toward the heart is against the direction of blood flow and involves much bending of the catheter near the heart, making the catheterization difficult. While ventricular pressures can be obtained via the aortic route, the atrial pressure is especially hard to obtain. For these reasons, indirect methods of measurement are desirable. Difficulties were encountered in the use of central venous pressure to estimate left heart pressures, and this led to the development of the pulmonary artery wedge pressure (PAW) measurement, which is considered to be an estimate of left atrial pressure.[1] For this measurement, the catheter is placed into a branch of the

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This thesis follows the style of the <u>Annals of Biomedical Engineering</u>.

pulmonary artery, and the pressure is measured just past a temporary block in the artery. This pressure is theorized to be left atrial pressure reflected back through the pulmonary circulation to this point. Considering the complexity of the system, this theory is too simplistic, and is also generally unsupported.

It would be helpful at this point to review the clinical method in further detail, so that the manner of obtaining PAW will be fully explained and can be visualized when considering the theoretical aspects. A balloon-tipped catheter, discussed by Swan, et al.,[2] is used to obtain the pressure measurement. The catheter contains two lumens along its length. The major, or larger, lumen is a liquid-filled connection between the opening at the catheter tip and the pressure transducer at the opposite end, outside the body. The minor lumen contains a gas, preferably CO_2, for inflation of the balloon near the catheter tip, as shown in Figure 1. A syringe is connected to this lumen at the other end, in order to push a known volume of gas into the balloon. The catheter is inserted using right heart catheterization.[1] It is introduced into an accessible vein, and threaded into the body. This path will eventually lead to the vena cava, and the right atrium of the heart. The balloon can be inflated at this point, so that the blood will aid in catheter insertion by carrying the balloon with its flow. As Figure 2 illustrates, the catheter is inserted further, so that it passes into the right ventricle and into the pulmonary artery. It is then pushed further into the branching pulmonary artery, until the balloon causes it to "wedge," and block flow in that branch from the right ventricle. The catheter tip, however, is past the balloon, so that the pressure past the blocked point is obtained. The sequence of pressures obtained as the catheter is threaded through the

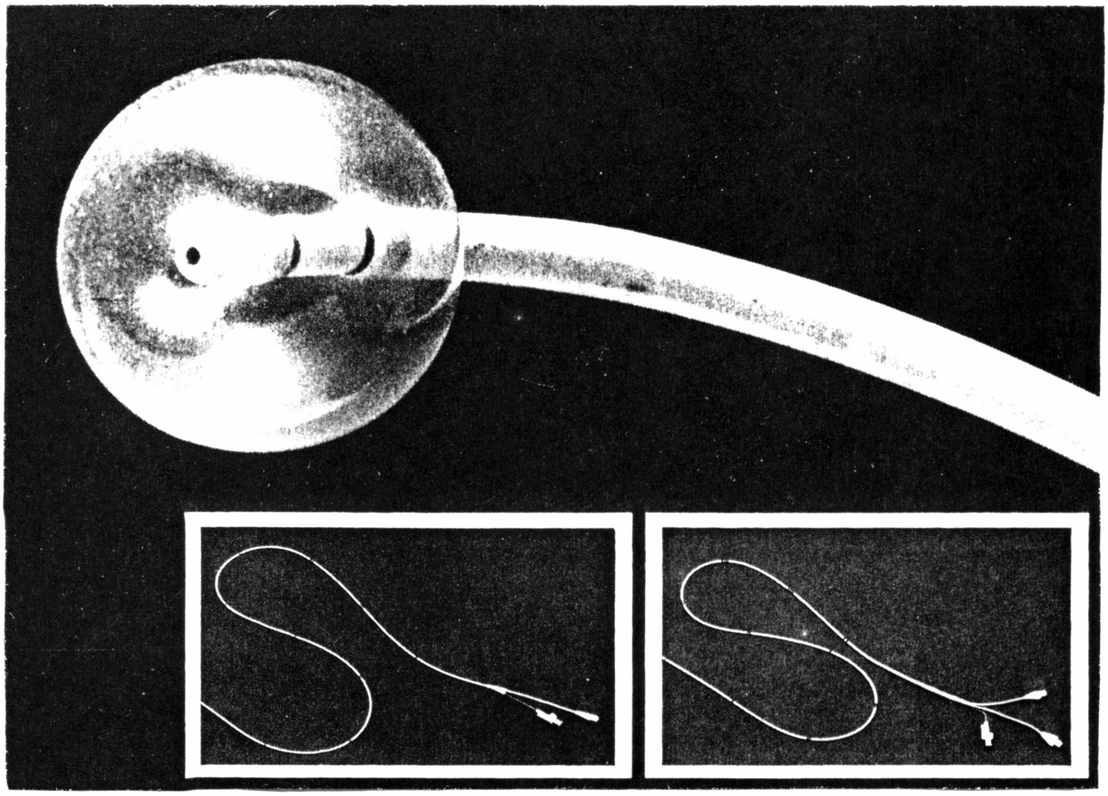

Figure 1

Swan-Ganz Catheter with Inflated Balloon.

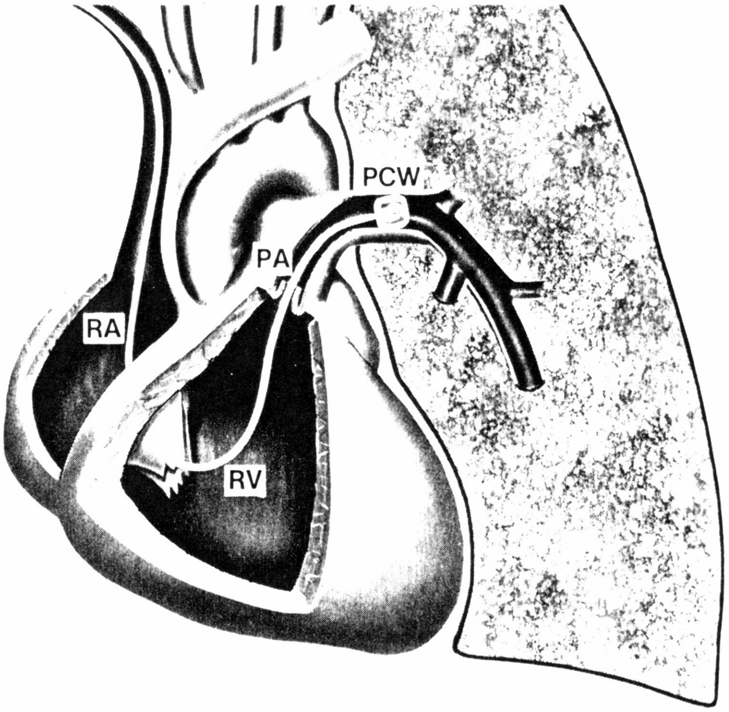

Figure 2

Swan-Ganz Catheter Balloon "Wedged" in Pulmonary Artery.

system, beginning with right atrial pressure (RA), is shown in Figure 3. After RA, the right ventricular pressure (RV) is seen, followed by the pulmonary artery pressure (PA), and, finally, the wedge pressure. The clinician assumes he is obtaining wedge pressure when a pressure waveform, similar to that shown, and to what he has obtained before, appears. This method is used both in the clinical setting, from which data for research is often obtained, and in experimental studies.

Pulmonary artery wedge pressure has been the topic of a significant amount of research; thus, literature is available concerning its relationship to many other parameters and conditions. Among these studies are: the use of PAW to predict left ventricular failure,[3] changes due to the use of positive end-expiratory pressure (PEEP),[4,5] relationship of PAW to colloid osmotic pressure in predicting risk of pulmonary edema,[6,7] and relationship of PAW to PA diastolic pressure with mitral stenosis.[8] Complications resulting from the use of the balloon catheter have also been studied.[9] The specific literature which is relevant to this study compares PAW to LAP for normal or pathological conditions, and studies in this category are shown in tabular form in Table 1, which shows the conditions worked under and conclusions reached for each investigator. All of these reports included statements on the relationship between PAW and LAP, while only some directly compared the two pressures experimentally, to reach their conclusions.

This project is basically concerned with the theoretical aspects of the wedge pressure measurement, or more specifically, the comparison of PAW to LAP. As stated previously, PAW is theorized to be essentially equal to LAP, through the assumption that the pressure directly past a blocked branch of the pulmonary artery is LAP reflected back through the

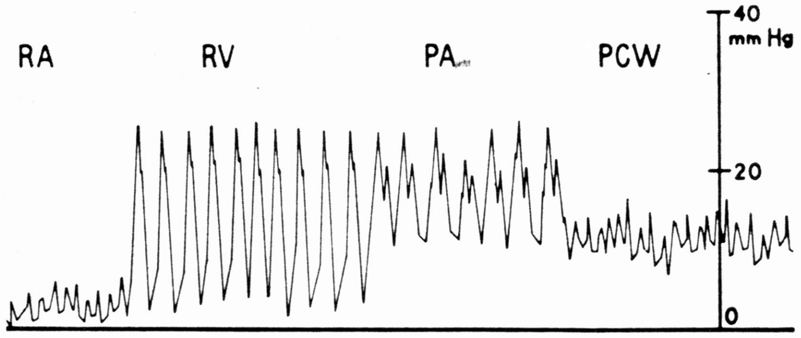

Figure 3

Pressure Sequence During Catheter Insertion.

TABLE 1

LITERATURE COMPARING PAW AND LAP

Investigator	Conditions	Conclusions
Gilbertson[1]	Article is basically instructional and a literature survey. Presents no data; assumes that PAW correctly indicates LAP.	States that the use of larger branches (for measurement of PAW) will result in a closer relationship between PAW and LAP, and less damping of the waveform.
Neville, et al.[4]	Measured LAP directly and PAW with Swan-Ganz catheter on 19 open-chested dogs, with 5 cm H_2O PEEP. Measurements obtained with catheter tip above, below, and at the level of the left atrium. LAP was "raised" by infusion of Ringer's solution, and "lowered" by bleeding to a mean arterial pressure of 40 mm Hg.	Measurement of LAP by PAW requires the system to be fluid-filled from the catheter tip to the left atrium. Erroneous measurements occur when catheter tip is above the level of left atrium. Pulmonary veins and capillaries below the LA are always patent. Elevated LAP ensures patency, even if PAW measured above the LA, and PAW is valid. As LAP falls, the number of nonpatent vessels increases, and probability of error increases.
Hobelmann, et al.[5]	Monitored PAW and LAP on six adult baboons, while positive end-expiratory pressure (PEEP) was administered (various levels). Study done because of possible detrimental effect of PEEP on cardiac output. Fall in CO associated with increased PAW.	Found that PAW and LAP were very different at high levels of PEEP; concludes that this was due to an impedance to flow between the pulmonary pre-capillary vessles and left atrium. Noted that other investigators concluded that increased alveolar pressure from PEEP collapses the pulm. capillaries, and so impedes capillary flow. Conclude that PAW may not reliably indicate LAP at any level of PEEP.

TABLE 1 (CONT.)

Investigator	Conditions	Conclusions
Fitzpatrick, et al.[10]	Studied 12 patients with congenital, rheumatic, or coronary disease requiring open cardiac surgery. Six of 12 had pre-existing pulmonary hypertension.	The larger the branch of the pulmonary artery blocked in PAW measurement, the better the correlation of PAW to LAP. PAW was concluded to be a "highly reliable index of mean left atrial pressure."
Walston, et al.[11]	Records of 700 patients (1959-72) obtained at cardiac catheterization were analyzed. Patients were grouped into normals (23), coronary artery disease (54), mitral stenosis (159), mitral insufficiency (39), and patients with more than one valvular lesion (310). LAP measured by transseptal left atrial puncture.	The prediction of LAP when PAW is above 10 mm Hg can be shown to have significant error. Mean PAW is a "moderately accurate predictor of mean left atrial pressure at these low normal wedge pressures." The loss of correlation stated above may be due to high pressures across the pulmonary capillary bed altering the ratio of arterial and venous compliance, resulting in asymmetric transmission of pressure waves.
Humphrey, et al.[12]	Monitored direct LAP and PAW on 43 patients who had undergone cardiac surgery (no PEEP used), for 48 hours.	The pooled correlation coefficient for PAW and LAP was 0.629. LAP was identical to PAW in 24% of cases, within ±1 mm Hg in 62.1% and within ±4 mm Hg in 94.6%. Found that left ventricular disfunction had no bearing on correlation. Indirect LAP measurements are a useful and reliable reflection of LAP.

pulmonary circulation. However, the pulmonary circulation, like the systemic circulation, has a very complicated arrangement, with the pulmonary artery branching into many smaller arteries, which branch into even smaller capillaries, which then rejoin into larger venules and veins, finally becoming the pulmonary vein. Considering this complexity, it is simply not apparent that the two pressure waveforms, or even their means, should be equal. The waveforms of PAW and LAP are not identical (Figure 4), while typical mean values are 8 mm Hg for PAW and 6 mm Hg for LAP.[13] Even at these accepted normal values, the PAW-LAP discrepancy of 2 mm Hg is 33% of the "correct" (LAP) value. This error is significant in itself, while the effect of disease on this difference has not yet been considered. The system under pathological conditions seems to be the most important, since PAW measurements are used clinically for diagnostic purposes.

It is reasonable, then, to reconsider the relationship between the two pressures. Although research has been done on the subject, most consists of isolated studies on segments of the population with specific conditions. The conclusions made by the individual investigators only have merit for each particular study, causing a multitude of results, which, in fact, often seem to be conflicting. This study, then, is an effort to apply an engineering analysis to the problem, by developing a model of the system. The model consists of the relevant parameters and variables, which can be manipulated, and thus used to represent the behavior of the system. Specific conditions can then be applied to the model, and comparison with the work and conclusions of the literature can be studied. Experimental surgery was also undertaken in this project. The purpose of the surgery, however, was not to generate a quantity of data that would be statistically valid, but rather, to generate some data that could be

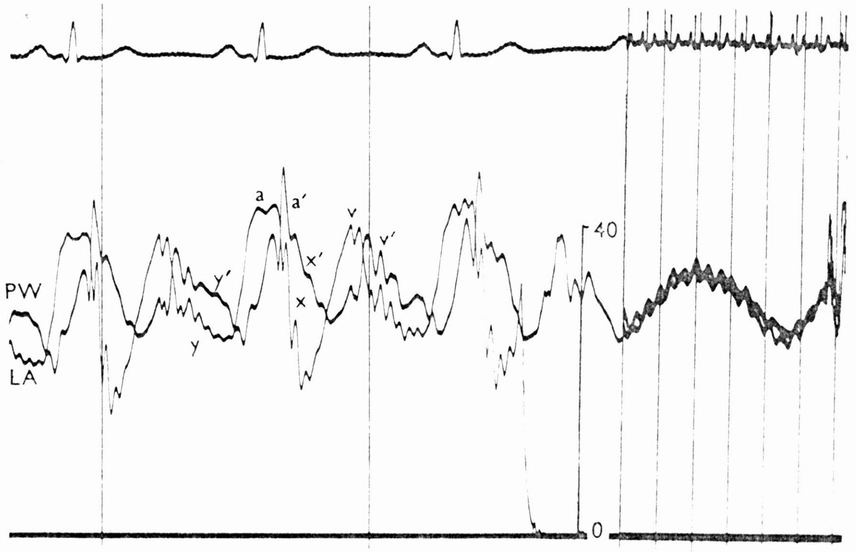

Figure 4

PAW and LAP Waveforms.[13]

analyzed for the sake of example, and to enhance the understanding of the clinical measurement procedure.

EXPERIMENTAL STUDIES

Surgical techniques used by Neville, et al.[4] formed the basis for the experimental surgery done for this study. Mongrel dogs, anesthitized with sodium pentobarbital, were used for the open-chest procedure. Positive pressure respiration was necessary to maintain breathing while the chest was open. A Swan-Ganz catheter, coupled to a pressure transducer and recorder, was used to obtain PAW. The catheter tip was introduced into the jugular vein, which was exposed by surgical cutdown, and the catheter was threaded into the vessel until reaching the desired point. Progress during this procedure could be seen by observing the waveform on the strip-chart recorder. Right atrial, right ventricular, and pulmonary artery pressures were seen before PAW. The latter was obtained when the balloon, inflated in the vicinity of the heart, became "wedged" in a vessel, and the typical PA tracing became the accepted PAW tracing (Figure 5). Direct LAP was also measured, by placing a catheter tip (no balloon) directly in the left atrium. The multi-channel recorder allowed both pressures to be observed simultaneously, as seen in Figure 6. The scales marked on the left side of the tracings are in the units of mm Hg, and were obtained by calibration with a mercury manometer, connected directly to the transducers. Both catheters were filled with heparinized saline, which was periodically flushed through the catheter. The baseline was checked periodically to avoid baseline drift. The large peaks in the tracings are due to the positive pressure respiration, which was necessary since the surgery was an open-chest procedure.

The basic purpose of obtaining data from this surgery was to compare PAW to LAP; mean pressure values are more suitable than dynamic waveforms

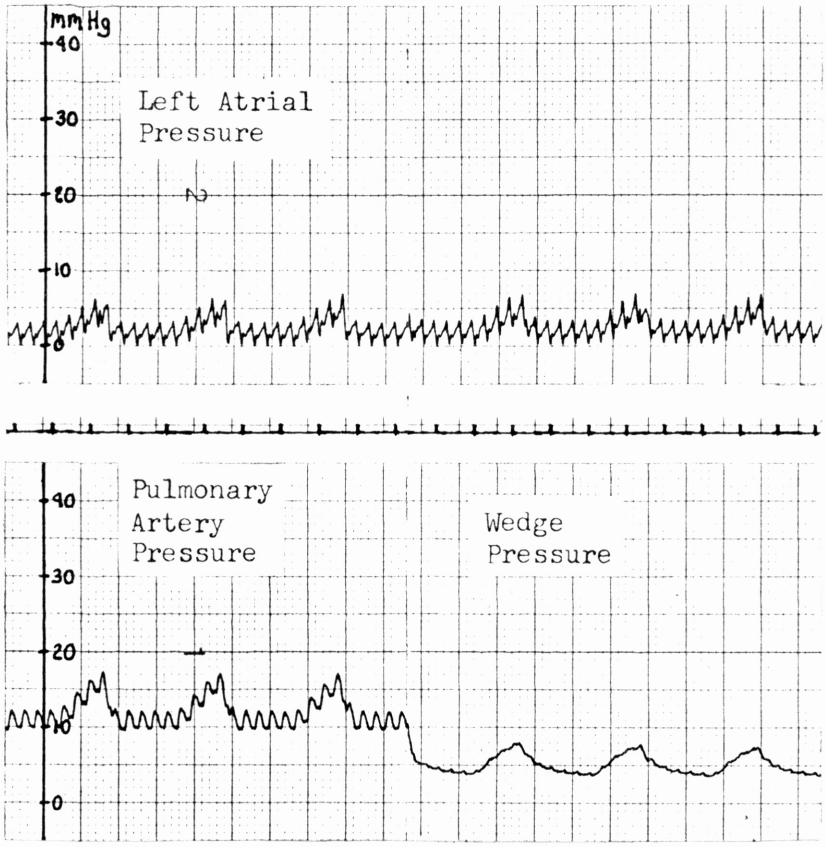

Figure 5

Left Atrial Pressure and Transition from Pulmonary Artery to Wedge Pressure.

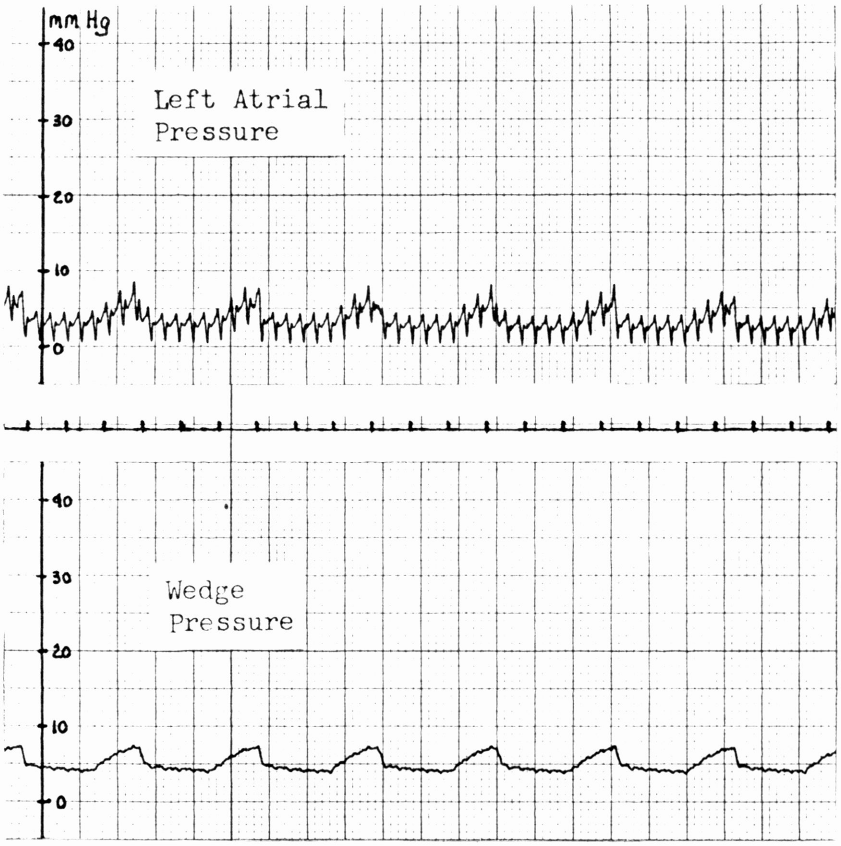

Figure 6

Steady State Left Atrial Pressure and Pulmonary Artery Wedge Pressure Waveforms.

for this purpose. Figure 7 shows the two tracings with the recorder on the mean mode. It can be seen that LAP is approximately 3 mm Hg, while PAW is approximately 5 mm Hg. These particular tracings, however, were recorded with a positive pressure respiration of 16 mm Hg. The level of positive pressure in the lungs was varied from 0 to 40 mm Hg, in order to observe any effects of this variable. The pressure was held constant, that is, no respiration was present. In Figure 8, the constant positive pressure (mm Hg) is given for each panel between the two tracings. It is evident that the two pressures are not equal to each other, but more importantly, it can be seen that the difference between the two pressures varies as the positive pressure varies. A graph of this result (Figure 9), with the PAW-LAP difference plotted against mm Hg positive pressure, shows the variation more clearly. The relationship appears to be generally linear in the range tested, and shows an increase in LAP relative to PAW as positive pressure is increased. No data was obtained in the "negative" pressure region, which would represent the actual closed chest, or usual clinical situation. These results indicate that positive pressure respiration has an effect on the absolute difference between the two pressures, and thus, is another variable to consider.

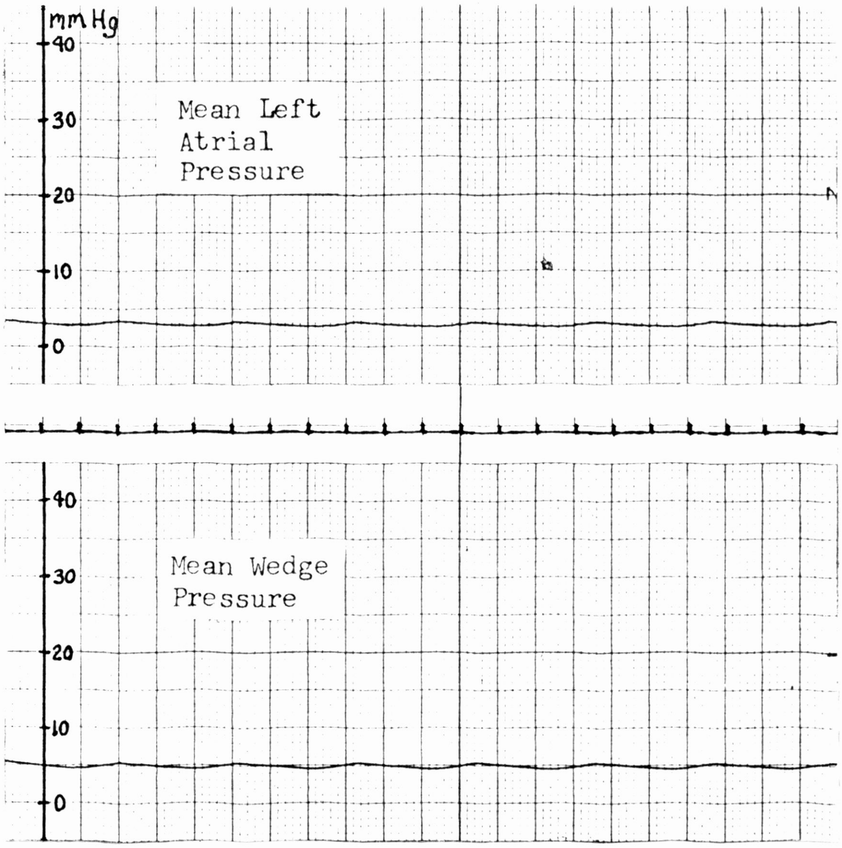

Figure 7

Mean Left Atrial Pressure and Mean Pulmonary Artery Wedge Pressure.

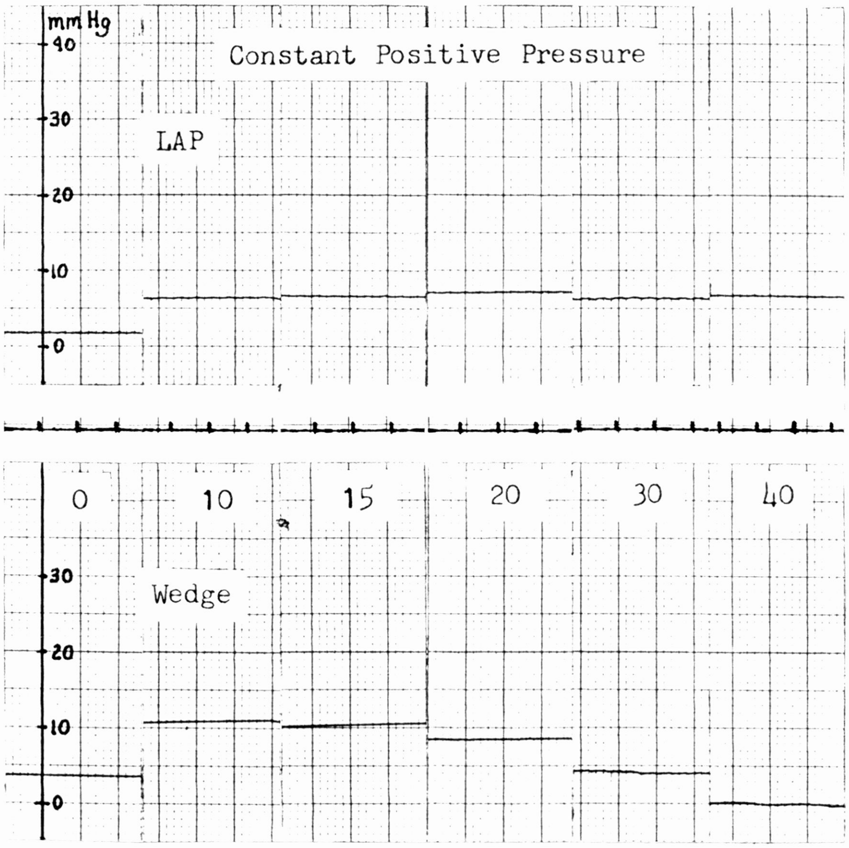

Figure 8

Mean LAP and PAW for Various Levels
(0-40 mm Hg) of PEEP.

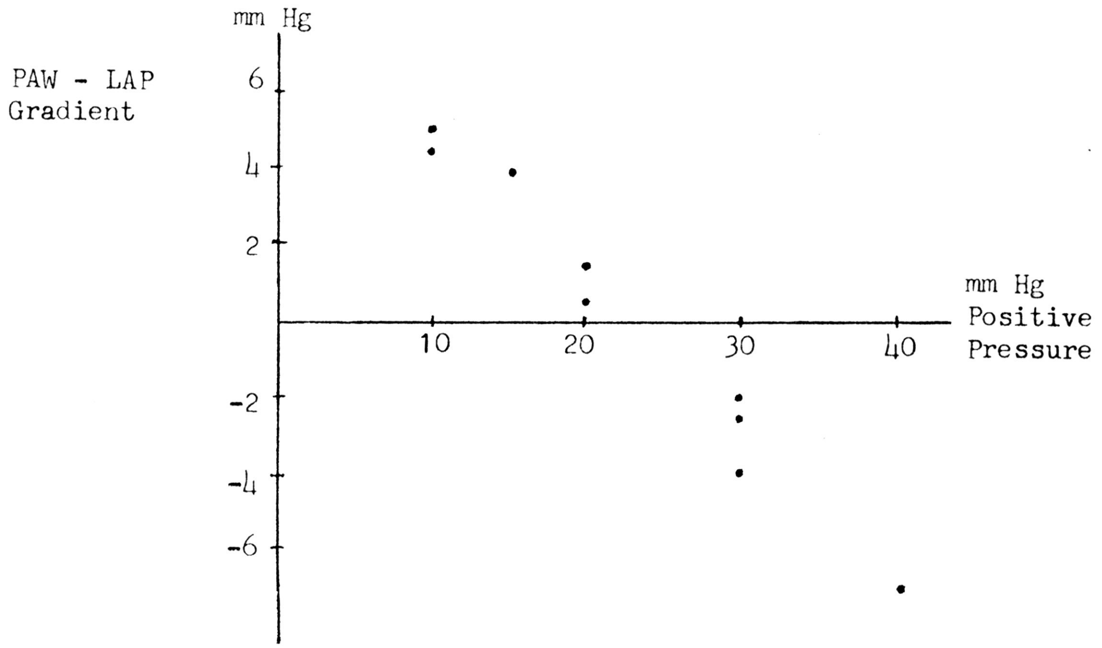

Figure 9

PAW-LAP Difference as a Function of PEEP.

MODEL

A model of the system under consideration is useful in any study involving a structured analysis. In general, the model is an attempt to specifically characterize a system, which may previously have been described only in subjective terms. Models may take the form of block diagrams, electrical analogs, mechanical analogs, and others, but are most useful to the engineer if mathematical analysis may be applied to solve for the unknowns in the system. For the vascualr system, models based on an electrical analogy have been found to be appropriate and relatively easy to work with. In this type of analogy, voltage is analogous to pressure, current to blood flow, electrical capacitance to vessel compliance, and electrical inductance to fluid inertia. Electrical resistance and viscous resistance are direct analogs. The model presented here only considers resistive elements. This is not a complete representation, but was chosen because of the mathematical complexity involved in adding capacitance and inductance, and the limited value of these added complications to the problem under consideration. With time-varying input functions, these properties require the use of differential equations, while resistive circuits generate algebraic equations.

The first model used was a very simple electrical circuit (Figure 10), which includes the basic physical qualities of the pulmonary circulation and the heart chambers involved. The voltage source V_s is analogous to the right ventricle, which is the pressure source for this system. The voltage V_2 represents the pressure in the left atrium. The pulmonary circulation is between these two points, with the left side the arterial section, the middle capillaries, and the right side veins. The parallel

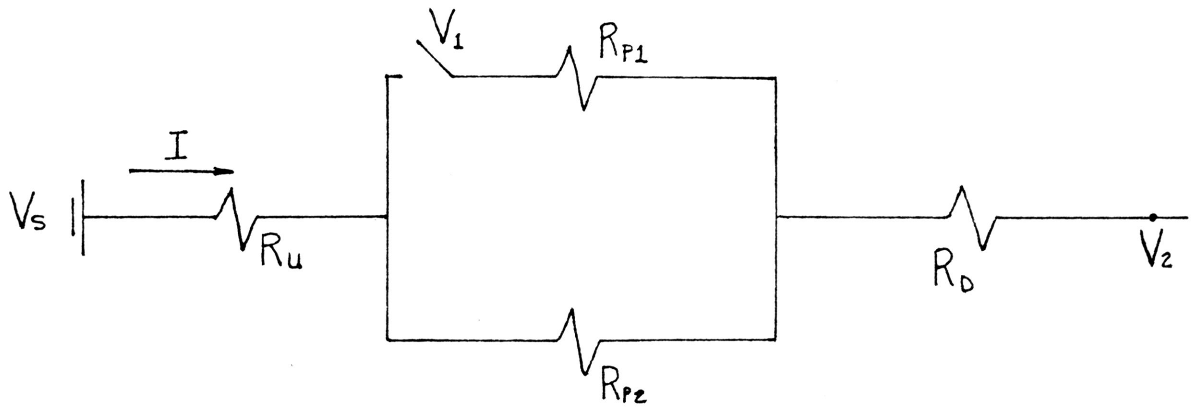

Figure 10

First Electrical Analog with One Level of Branching.

section is included to simulate the branching and rejoining that is characteristic of the pulmonary circulation. The voltage V_1, which is labelled at the switch, represents a possible point of measuring wedge pressure. The switch is present because the wedge pressure measurement blocks forward blood flow while the balloon is inflated, and the analogy requires an open circuit for this case. The voltage V_1, when the switch is open, is actually the voltage at the point A, shown on the figure. This observation provides the first important concept, which is that the wedge pressure is actually the pressure where the stagnant path distal to the balloon is in contact with the next flowing channel. This generalization is true, regardless of the complexity of the actual system.

This model is a "lumped-parameter" model, since the continuous property of viscous resistance is lumped into discrete resistive elements. Also, however, the resistance values are lumped, in that they actually represent the combined resistance of many branches, relative to the point of measurement. The resistances R_u and R_d are subscripted to indicate resistance upstream and downstream of point A, respectively, while the parallel resistances R_{p1} and R_{p2} are distinguished from each other since they would not necessarily be equal.

The model was used to generate a comparison of wedge pressure to left atrial pressure, or V_1/V_2. This was accomplished through the use of simple electrical circuit theory and mathematical manipulation. According to Ohm's Law,

$$V = IR, \tag{1}$$

where V is voltage, I current, and R resistance. Using (1), two basic equations are obtained:

$$V_1 - V_2 = IR_d, \tag{2}$$

and $$I = (V_s - V_2)/(R_u + R_{p2} + R_d). \tag{3}$$

The sum of resistances in equation (3) does not contain R_{p1}, since taking a wedge pressure measurement is modelled by an open circuit at V_1, and, thus, no current flows through the upper branch. Equation (3) is then substituted into equation (2) and manipulated, to obtain

$$V_1/V_2 = 1 + ((\alpha - 1)/(R + 1)), \tag{4}$$

where $\alpha = V_s/V_2$ and $R = (R_u + R_{p2})/R_d$. This shows that the relationship between PAW and LAP (V_1 and V_2) is more complex than the simple theory discussed previously would indicate. The "R" term contains both upstream and downstream resistances, which is due to the flow or current being affected by the entire system. The relationship between "R" and V_1/V_2 is shown in Figure 11. Note that when $R = 0$, $V_1/V_2 = \alpha$, and when $R \rightarrow \infty$, $V_1/V_2 = 1$. It is easily seen, then, that more accurate wedge pressure measurements (V_1/V_2 closer to unity) are obtained for large R and small α. The measurement is most accurate, then, for $(R_u + R_{p2})$ large in comparison to R_d, and for a small total pressure drop.

Another important concept is that even though this equation may not be applicable in a strict sense, to the actual situation, it does show the relationship between the analogs of wedge pressure and left atrial pressure for this particular circuit model. This implies that an analogous equation could be generated for another model, especially a more complex one, which would perhaps be closer to reality. A slightly more complicated model, with two branchings (Figure 12), was also analyzed. As before, V_s is the right ventricular pressure, and V_2 is left atrial pressure. The wedge pressure, however, has two possibilities for points of measurement, V_1 and V_1', which are actually at two different levels of

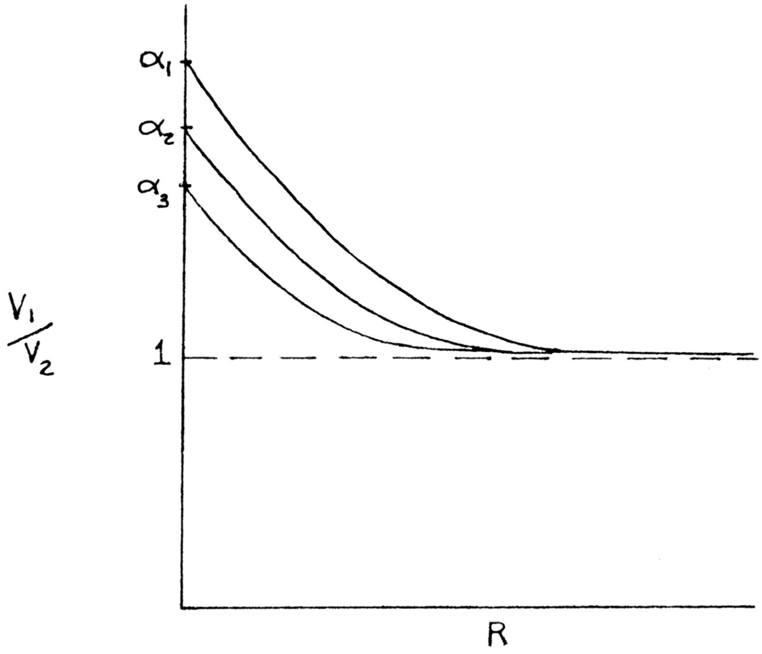

Figure 11

V_1/V_2 (Analog of PAW/LAP) Versus Resistance Term for Several α Values.

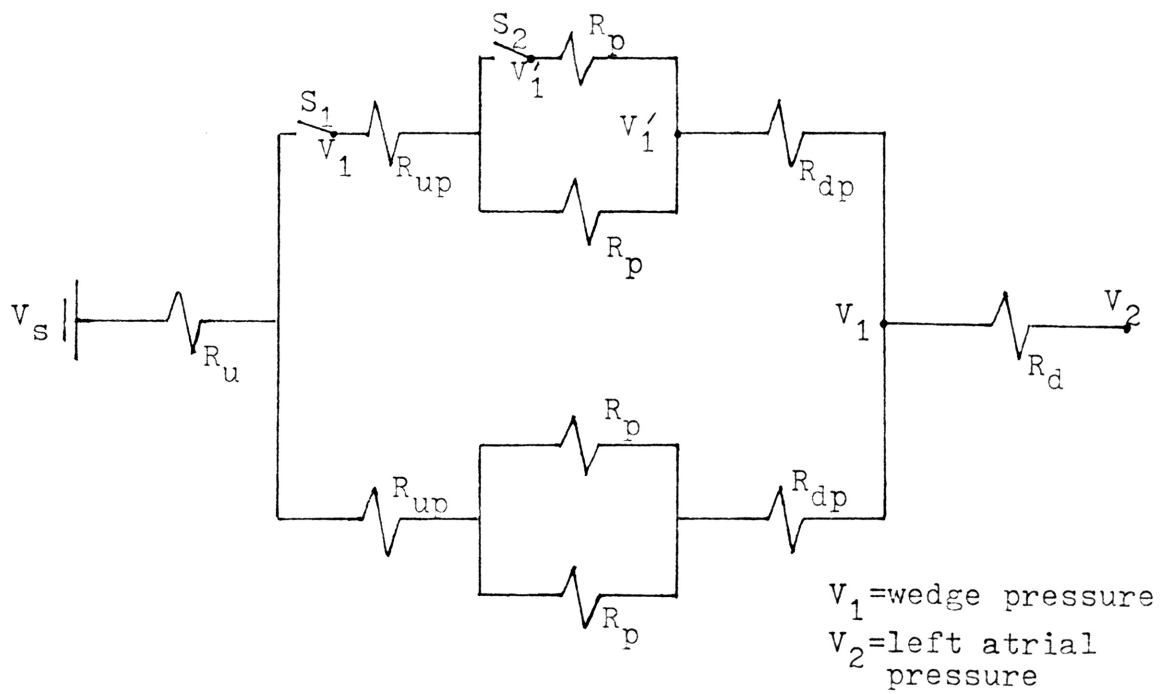

Figure 12

Second Electrical Analog with Two Levels of Branching.

branching. Using this model, V_2 could be compared to V_1 or V_1' for each of the two cases. The first case is with S_1 open, so that a larger artery is blocked, while the second case is with only S_2 open, and a smaller artery is blocked. Using the same procedure employed with the first model, expressions were obtained for V_1/V_2 and V_1'/V_2. The two results can both be put in the form

$$V_1/V_2 = 1 + ((\alpha - 1)/(R + 1)). \tag{5}$$

However, the "R" terms are different in the two cases. In

$$\text{Case 1:} \quad R = (R_u + R_{up} + R_p/2 + R_{dp})/R_d, \tag{6}$$

and in

$$\text{Case 2:} \quad R = (2R_u + R_{up} + R_p/2)/(R_{dp} + 2R_d). \tag{7}$$

Comparison of the R terms shows that equation (6), or Case 1, has the larger R, which would give a smaller $(\alpha - 1)/(R + 1)$ term, and in turn, a V_1/V_2 that is closer to unity. This model shows, then, that measurement in a larger artery is more accurate.

It was necessary at this point to determine if, in fact, analysis of a more complex model would be worthwhile. A totally realistic model of the pulmonary system was seen to be an impossibility for the purpose of this study. The problem stems from the fact that the pulmonary circulation is a system of apparently randomly-branching tubes, which does not seem as though it could be adequately represented by "combined" resistances, especially when the internal details are critical to the result sought. Since the mathematical analysis associated with a more complex model would be tedious, it would be worthwhile only if a model were found which represented any branching complexity. Vessel branches which bypass the point where the blocked vessel rejoins a flow path, are an example of a case difficult to account for in a lumped variable. Since the model is not completely realistic, expressions directly applicable to the clinical setting cannot be obtained. The model is, however, still a very valuable tool, which can be used to integrate clinical observations from studies in the literature, and to explain the basic principles of the measurement in a consistent manner.

DISCUSSION

The model, then, actually represents the pulmonary circulation and so can be used as a reference for comparison with the literature. The conditions for each study and the results can be related to the model, and therefore, conclusions can be formed more easily and within a consistent conceptual framework. This is true for both individual studies, and for the comparison of studies with differing conditions. The effect of all parameters on the general behavior of the system can also be studied through the use of the model, and the reasons behind various experimental results then became more apparent.

The first concept that will be considered concerns the relationship between the pulmonary artery vessel size and the accuracy of the PAW measurement. Statements concerning this relationship were found in the literature. The study by Fitzpatrick, et al,[10] in which PAW and LAP were monitored on 12 patients requiring open cardiac surgery, reported that "In general, the larger the pulmonary arterial branch occluded, the greater the similarity of the $P_{pa_{occl.}}$ tracing to the P_{la} tracing."[10] Gilbertson[1] also states that this phenomenon exists, adding that the damping of the wave form will be smaller when a larger artery is used.

To study this concept, the second model (Figure 3), involving two levels of branching, was analyzed. The two possibilities, PAW in a large artery (V_1), and PAW in a smaller artery (V_1'), were studied and the results discussed previously. Comparison of the two expressions, V_1/V_2 and V_1'/V_2, revealed that V_1/V_2 would always be closer to unity than V_1'/V_2. Thus, according to the model, PAW would be closer to LAP for a larger artery. This is due to the fact that more of the vessels between the point of PAW and LAP are included for measurement in a larger artery, and therefore the distal end of the blocked segment will be closer to the left atrium. The model results, then, agree with the literature conclusions, and also give the underlying relationships.

The second concept, which became apparent after development of the model equations, is the importance of the method of comparison. Consideration of the most appropriate form for the model equations led to the realization that the relative magnitude of PAW and LAP should be compared. Many investigators seem to only consider absolute differences. However, while the value for $(V_1 - V_2)$ may be small, the V_1/V_2 value may not be near 1, as is necessary for an accurate measurement. It should be noted that the correlation coefficient (r), calculated in many studies, is simply an indication of a linear relationship exhibited by the data, so that a high r value (close to 1) indicates little scatter. This statistic has little to do with how well PAW indicates LAP. Walston and Kendall[11] show expected (95% confidence limit) PAW-LAP differences for various PAW ranges. The interval of values within the 95% confidence limits increases both absolutely and proportionally with increasing PAW. The authors conclude from their results that "mean pulmonary wedge pressure is a moderately accurate predictor of mean left atrial pressure at these low normal wedge pressures,"[11] referring to a PAW of 10 mm Hg or less. However, they present a ±2 mm Hg expected interval for low normal PAW. The error could be 20%, and this may be significant. Therefore, the apparent acceptability of PAW at low normal pressures may be due to the lack of a proper comparison. The study by Humphrey, et al.,[12] in which LAP and PAW were monitored on 43 patients who had undergone cardiac surgery, presents certain PAW-LAP differences and, the percentage of time these differences existed. LAP was identical to PAW in 24% of the cases, within ±1 mm Hg in 62.1%, and within ±4 mm Hg in 94.6%. For the last case, which is similar to the 95% confidence limits just discussed, a 4 mm Hg difference would be 26.7% of a mean LAP of 15 mm Hg.[11] This is not an insignificant value, yet the authors conclude that indirect LAP is a reliable reflection of LAP. Thus, the development of the model demonstrates the importance of the method of comparing PAW and LAP.

A specific example of comparison between the model and parameters studied in a particular investigation can be demonstrated with the study by Hobelmann, et al.[5] This group studied the effect of positive pressure respiration (PEEP) on PAW and LAP monitored on baboons, and found that the two pressures were very different at high levels of PEEP. This effect can be considered with reference to the graph of the model equation (4), or $V_1/V_2 = 1 + ((\alpha - 1)/(R + 1))$, shown in Figure 13. It must be remembered that the α values (V_s/V_2) are generally considered constant for a particular measurement. Two main effects of high levels of PEEP can be simulated on this graph. First, it may be assumed that since the veins would be more susceptible to collapse under pressure than other blood vessels, R_d would increase more than the other resistance values. This idea is also stated by Walston and Kendall: "high pressures across the pulmonary capillary bed cause a change in the ratio of pulmonary arterial and pulmonary venous compliance."[12] Thus, the ratio of resistance would change, and the term $R = (R_u + R_p)/R_d$ would decrease. On the graph, then, as R decreases (indicated by arrow), this would move to a new state on the same α curve, which would have a V_1/V_2 farther from one. This indicates a less accurate measurement. A second effect of high PEEP could be a decrease in LAP (V_2) due to the assumption that total resistance in the vessels

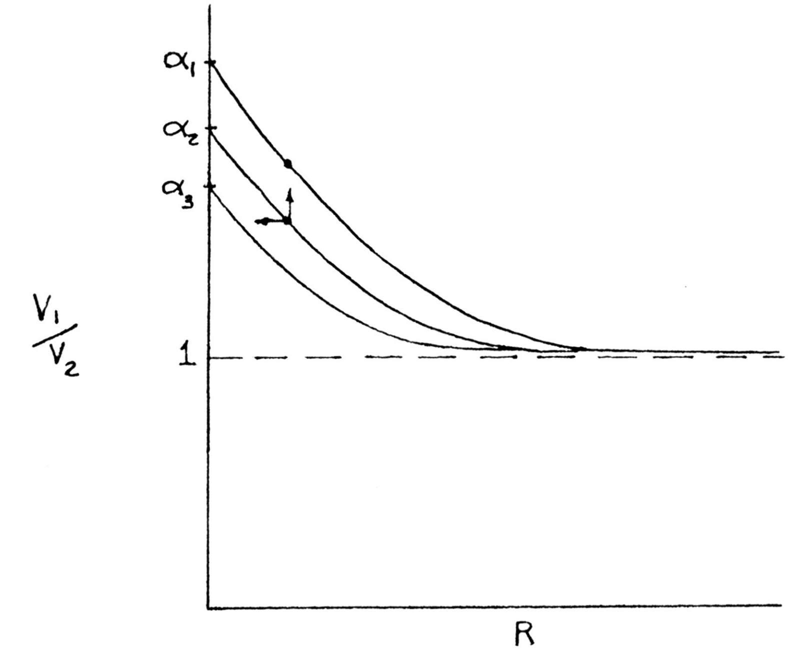

Figure 13

V_1/V_2 Versus Resistance Term for Several $\propto$ Values with Changes Indicated.

increases. If V_2 decreases, the value of α would increase. Considering this on the graph, the new state would be on a higher α curve. If it is assumed that the ratio of the upstream and downstream resistances is not changed, then the new system state will be at a point directly above the previous state. Again, this gives a V_1/V_2 farther from the ideal value of one, and indicates PAW farther from LAP. The combined effects would give an even greater elevation from one. These model results agree with the observations made by Hobelmann, et al.[5] and also show possible reasons for these results.

A final application of the model to a particular study concerns the work done by Neville, et al.[4] This study involved the measurement of direct LAP, and PAW on 19 open-chested dogs on PEEP. The effect of different levels of LAP on the PAW to LAP relationship was considered. They obtained significant differences in the two pressures at normal LAP (PAW-LAP = 6.5 mm Hg) and at low LAP (PAW-LAP = 9.4 mm Hg). This was attributed to the fact that an elevated LAP would ensure patency of the vessels (low resistance), while as LAP is lowered, the number of patent vessels decreases, primarily due to venous collapse, and the error increases. As noted before, increased venous collapse would cause R_d to increase, and R to decrease. This is the same as the first effect in the PEEP example. Considering Figure 13, as R increases, a higher value of V_1/V_2 results, following a constant α curve, and the measurement is less accurate. Feedback may also be involved if R_d decreases to the extent that V_2 (LAP) is lowered, thus causing a further increase in nonpatent vessels.

CONCLUSION

The use of pulmonary artery wedge pressure as an indication of left atrial pressure for diagnostic purposes suggests consideration of the relationship between the two pressures. The literature on this subject, however, consists of individual studies where varying conditions and specific population samples make comparison difficult. Thus, conclusions formed from the results of these studies were not generally applicable. Also apparent was a lack of understanding concerning the system itself and the roles of PAW and LAP. The engineering approach to this problem, the formation of a model, is helpful in both regards. It represents the system in terms that are commonly studied (electrical parameters) and to which definite laws can be applied. This allowed the generation of a mathematical expression and graphed equivalent. By studying these, the actions of the general system (pulmonary circulation) and underlying reasons can be more easily seen. The model, then, is first an educational tool to gain understanding of the system and its operation. Second, however, the model can be used to study results and conclusions in individual studies and determine if the experimental results agree with the model. It is then possible to consider all cases, even though test conditions may have been vastly different and previously incapable of comparison. The model is, then, both a point of reference and a vehicle for understanding results.

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